



DOCUMENT 322-98

**GUIDELINES DOCUMENT:
GLOBAL POSITIONING SYSTEM (GPS)
AS A
REAL-TIME FLIGHT SAFETY DATA SOURCE**

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**GPS Range Safety Applications Ad Hoc Group
Range Commanders Council**

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PREFACE

The primary objective of the Global Positioning System (GPS) Range Safety Applications Ad Hoc group was to evaluate the use of GPS as a real-time flight safety data source and to provide guidelines for its implementation at the RCC ranges. The ad hoc group's findings indicate that GPS technology, as it stands today, is capable of furnishing an excellent data source for flight safety decision-making. The group found that some ranges are already using GPS as a tracking source on various types of vehicles and in some cases ranges are using GPS as the primary data source. It is anticipated that ranges will most likely be using GPS as a primary flight data source in the very near future. The group also found that many users are implementing GPS as part of their guidance and navigation support capabilities. When properly designed, these user systems can also provide data for flight safety purposes. When compared to other metric sources, GPS has many advantages; however, no single data source, even GPS, yields a complete safety solution under all test conditions. Therefore, it is wise for range planners to consider an optimal mix of GPS, radar, inertial data, and optics instrumentation, depending on the specific application.

This guidelines document was written specifically to assist flight safety and other range support personnel in implementing GPS as a real-time safety data source. However, it also provides information to the range manager who is involved in transitioning a range to GPS and to range users who are considering incorporating GPS as a tracking source on their test vehicles. This document includes a brief discussion of the overall flight safety test management process and the requirements placed on any metric data source when that source is to be used for real-time safety decision making. A basic description of how GPS works, as well as a discussion of various types of GPS configurations and antenna systems, is included. These guidelines also address potential problems that could affect the reliability of GPS as a tracking source and provide suggestions for mitigating their impact. The group also documented several examples of programs that are currently using GPS or plan to use GPS in the near future, including a discussion of lessons learned specific to each example. Also included is a general discussion of lessons learned that can be applied to the use of GPS as a safety tracking source. Lastly, this guidelines document describes a process by which the ranges can evaluate or assess GPS systems as a metric data source for real-time flight safety decision making. The key to this process is the evaluation and testing of the GPS system and the use of dynamic simulations.

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Summary and Recommendations

GPS Range Safety Applications Ad Hoc Group Members/Participants

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CHAPTER 1

INTRODUCTION

1.1 Document Purpose

This document provides guidelines for utilizing the Global Positioning System (GPS) as a real-time flight safety metric data source. This document is not intended to be an operating standard or specification for range support or GPS equipment. Instead, these guidelines contain information that will assist range personnel in determining if a GPS configuration is adequate for flight safety support.

1.2 Document Scope

The guidelines in this document were prepared by the RCC GPS Range Safety Applications Ad Hoc Group, and are intended for use by Department of Defense (DOD) National Ranges and Major Range and Test Facility Base (MRTFB) ranges and facilities. They are written specifically to assist Flight Safety and other range support personnel in implementing GPS as a real-time safety data source. The document also provides considerations for the range manager involved in transitioning a range to GPS tracking. This document serves to provide the range user with an understanding of the fundamental safety requirements and the process by which ranges should evaluate a user-provided GPS tracking system for safety purposes. The document also provides design considerations for the range user when developing a GPS configuration that will not only meet program needs, but will also satisfy flight safety requirements.

1.3 Ad Hoc Group Membership

Ad hoc group membership was open to all Range Commanders Council (RCC) ranges. Representatives to the ad hoc group were provided by the following ranges: White Sands Missile Range, Western Range, Air Force Flight Test Center, Naval Air Warfare Center Weapons Division (Pt Mugu and China Lake) and Kwajalein Missile Range. These members were affiliated with the RCC Range Safety Group, Electronic Trajectory Measurements Group, and Documentation Group. The ad hoc group also included representatives from Aerospace Corporation, ITT Federal Services, and ACTA Inc. The Range Instrumentation Systems Program Office (RISPO), formally known as the Range Applications Joint Program Office (RAJPO) also supported this task and the Department of Transportation (DoT) provided a link to the commercial space transportation sector. Members of the ad hoc group were experienced in many different aspects of testing including flight safety, GPS, instrumentation development and testing, data analysis, and radar transponder and flight termination system testing and certification. A list of official ad hoc group members and others who provided technical support is at enclosure 1.

1.4 Task Background and Approach

The GPS Range Safety Applications Ad Hoc Group was formed early in 1996 in response to a task proposal (reference 1). The primary objective of the group, as stated in the task proposal, was to "define guidelines and requirements for utilizing Global Positioning System (GPS) as a real-time range safety data source." The ad hoc group had its initial meeting in March 1996 to define the task objectives and approach. During this meeting each of the members briefed the group on GPS activities related to flight safety at their respective ranges. To gain knowledge of GPS activities at ranges not represented, the group prepared a data gathering survey (reference 2) and sent it to all RCC member ranges. The survey was in the form of the following six questionnaires:

- Vehicle Dynamics
- Range GPS Real-Time Configurations
- Qualification, Acceptance and Validation
- GPS On-Board Configurations
- Real-Time Processing and Display
- Post-Mission Processing

In addition to the above survey, the group invited vehicle contractors to several meetings to discuss upcoming flight tests carrying a variety of GPS experiments. Group members also visited GPS simulation facilities at both Holloman AFB and Ft Huachuca. A total of nine official meetings were held over the 20-month period of this task, and for several months the group had weekly conference calls. The information provided in this document is based on the GPS survey responses, briefings, mission analysis, and numerous GPS studies (see references 3 – 11). The lessons learned from these inputs and the experiences of the group members contributed significantly to the contents of this document.

Although the task proposal called for the development of "guidelines and requirements," it became evident that only "guidelines" could be provided within the limited time period and funding available to complete the task. In addition, several other considerations drove the development of guidelines versus requirements. While GPS was being used at many ranges, in some cases there was a great deal of reluctance by some Flight Safety Offices to adopt GPS as a flight safety tracking source. There were also many different configurations being utilized, and GPS technologies were changing quite rapidly. Therefore, the decision was made to produce a document that provides "guidelines" for implementing GPS, not a standard.

A process is identified in Chapter 6 by which GPS systems can be approved for use as a real-time safety data source. A follow-on effort is recommended which would identify "requirements" or "standards" for environmental qualification, functional, and performance evaluation testing of GPS systems, as well as requirements for the development of dynamic simulations.

CHAPTER 2

FLIGHT SAFETY REQUIREMENTS

This chapter is intended to give the reader a better understanding of the overall flight safety test management process and the requirements placed on any metric data source when that source is to be used for real-time safety decision making.

2.1 Flight Safety Test Management

The flight safety test management process is a function of the range, vehicle under test, mission scenario, and other safety constraints. This process, though basically the same at most ranges, often varies among ranges due to the geographical or other limitations of each specific range. However, the fundamental safety requirement at all ranges is the same: protection of life and property. A secondary objective is the assurance of mission success. All tests are potentially hazardous and involve some level of risk. The underlying safety test management process is predicated on taking all prudent and reasonable steps to minimize the level of risk to the general public, to mission essential personnel supporting the test operation, and to the test program. This is accomplished through the safety management process, which typically consists of pre-mission safety planning and real-time safety test management. Pre-mission safety planning begins with the evaluation of test hazards based on specific vehicle system characteristics, performance, flight profiles, and failure modes. Part of the planning effort involves the development of methods to lower risks to acceptable levels by various techniques (e.g., limiting flight scenarios, implementing flight management systems or flight termination systems, etc).

Real-time flight safety test management requires monitoring of vehicle performance in-flight by the Range Safety Officer (RSO). The term "RSO" is used generically in this document to designate the individual or individuals responsible for making in-flight safety decisions, particularly flight termination decisions. During real-time, the RSO is delegated the authority to implement the Range Commander's flight safety policies and has sole responsibility for making safety decisions. In those instances where a vehicle failure occurs in-flight, the RSO assures low risk to life and property by terminating or constraining flight before an unsafe condition can occur. The RSO can also terminate or constrain flight if positive assurance is not provided that the flight is proceeding in a safe manner. Displays derived from metric data are critical to the RSO's decision-making process. In many cases, failure of the tracking source or failure to properly process and display the information, will lead to a flight termination action to assure protection of life and property.

2.1.1 Metric Data Sources. Traditionally, information displayed for the RSO has been derived from various data sources like video, optics, outside observers, telemetry based systems, and radar. In recent years, due to stressing missions or limited range tracking sources, inertial guidance data from the vehicle under test has been used as a metric data source. Inertial guidance data is very responsive and provides low noise position, velocity, and attitude information. However, a closed loop inertial guidance system (the system that steers the vehicle)

can fail in such a way that the data indicates the vehicle is flying nominally when it is not (e.g., platform misalignment). Such failure modes may constitute a risk to life and property and, as such, are of great concern. To assure low risk to life and property, some ranges, depending on the mission scenario, require validation (both pre-mission and in-flight) of inertial guidance data by another metric source prior to its use as a flight safety data source. In some cases, inertial guidance data is validated with range radar data. It can also be validated by other metric sources such as GPS or an independent inertial measurement unit (IMU).

2.1.2 Real-Time Flight Safety Information. Flight safety data processing and display formats vary from range to range and vehicle to vehicle depending on many factors. Each range performs measurement and display of tracking data in ways that best suit its mission and flight profiles. For example, metric displays may be used to allow release of a test item such as a bomb based on aircraft position, or the displays may be used to provide tracking data on a spacelift vehicle from launch to orbit insertion. Typical information displayed for flight safety includes:

- **Vehicle Time, Space, Position Information (TSPI)** - Almost all missions require the display of vehicle TSPI. This information may be displayed in various ways including present position, velocity versus time of flight, and altitude versus ground range.
- **Instantaneous Impact Point/Prediction (IIP)** - Vehicle position and velocity are used to estimate the impact location of the vehicle or debris given a failure or termination action. Not all vehicles or missions require display of an IIP. The requirement is highly dependent on vehicle performance and dynamics.
- **Vehicle Attitude** - For some missions, display of attitude information may be critical to making real-time decisions. Attitude information is not typically provided by radar or GPS, but can be provided from IMU or inertial guidance measurements.
- **Vehicle Performance** - Performance data typically refers to such information as fin positions, chamber pressure, staging events, etc.
- **Health and Status** - Real-time monitoring of health and status information by the RSO is also important to verify that the measurements provided by the tracking source are credible.

2.2 Flight Safety Data System Requirements

Ranges often place stringent performance and reliability requirements on metric systems that provide information for flight safety. Systems in this context include associated vehicle modules or equipment, range support equipment, and range flight safety processing and display equipment. It was not the intent of the ad hoc group to identify a standard set of data system requirements or to identify specific "numbers" associated with the reliability requirements. This document simply states the basic general requirements that are used at most ranges. The extent to which these requirements must be met depends on vehicle kinematics and range constraints, while also balancing mission risk and costs.

- **Reliability** - The basic requirement at each range is for a reliable metric data source that will ensure the RSO has the necessary information to make critical real-time safety decisions. Ranges may specify definitive reliability criteria, such as 0.995 at the 95 percent confidence level for all missions or for specific missions.
- **Independence** - Reliable support is achieved at most ranges through the use of independent metric sources. Independence means that a failure of one metric system will not degrade another metric system. Most ranges have a requirement for two independent tracking sources. There are exceptions and, again, they are based on vehicle performance and range constraints.
- **Redundancy** - To demonstrate vehicle module reliability, it is often necessary to use a design which provides redundancy. Similarly, range support equipment must be designed, sited, and operated in such a way as to meet high system reliability requirements. Typically, redundant range assets with geographical separation are used to ensure adequate coverage. Redundant flight safety processing algorithms and displays may also be required.
- **Metric Data Characteristics** - Metric data characteristics of interest to flight safety include data precision, accuracy, latency, and sample rate.

CHAPTER 3

GPS BASED METRIC SYSTEMS

This chapter is intended to provide the reader a basic understanding of how GPS works by describing the GPS Control, Space, and User Segments. The Vehicle Subsystem section of this chapter includes a discussion of various types of GPS configurations and antenna systems. The range systems that support many of the GPS systems are briefly described in the Range Subsystem section.

3.1 GPS Based Metric System Description

The Global Positioning System consists of three segments: the Control Segment, the Space Segment and the User Segment. The Control Segment basically maintains the GPS satellite constellation. It monitors satellite health and performs satellite housekeeping including ephemeris and clock uploads, periodic maintenance, and on-orbit relocation. It also notifies the user community of planned and actual changes in the satellite constellation. The Space Segment accepts housekeeping updates from the Control Segment and provides the GPS signals. The User Segment is intuitive; it extracts the ephemeris and satellite status, generates pseudo range measurements from code track and generates delta pseudo range measurements from carrier track to develop estimates of time, position, and velocity. In most range applications, the User Segment typically consists of range user equipment on the flight vehicle and range equipment to acquire and process the GPS provided information. The ad hoc group has adopted the following terminology for this document. Each GPS based metric system includes three generic subsystems; the Space Subsystem (equivalent to the Space Segment), the Vehicle Subsystem, and the Range Subsystem.

There are two basic types of GPS based metric systems as illustrated in Figure 3-1, a translator system and a receiver system. The fundamental difference between receivers and translators is the physical location of the processor. Receivers include the processor on the vehicle, while translators downlink the frequency translated GPS signals to an off-board processor. Another significant difference is the downlink bandwidth. Translators require more bandwidth than receivers. The downlink can be transmitted using conventional range telemetry or dedicated downlink modules.

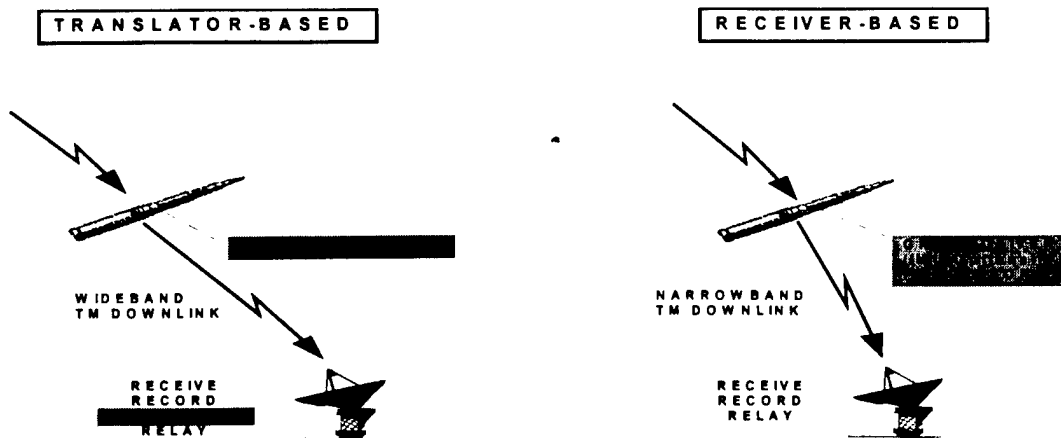


Figure 3-1. GPS Based Metric Systems

3.2 Space Subsystem

The core of the Space Subsystem is a constellation of orbiting satellites. There are 24 satellites arranged in six orbital planes circling the earth at approximately 10,900 nautical miles. Each satellite transmits coded L-band signals containing information such as the satellite's ID, clock correction, ephemeris, and health. The transmit frequency and code are synchronized to an on-board atomic frequency standard. The signals consist of a one megabit/sec C/A code on the 1.5 GHz L_1 frequency (with optional selective availability (SA)) and 10 megabit/sec P(Y) code on the 1.5 and 1.2 GHz L_1 and L_2 frequencies. A restricted one megabit/sec C/A code on the 1.3 GHz L_3 frequency is authorized for the US Navy Trident II program. A 50 bit/sec message containing ephemeris and status is modulated on the GPS signal carrier. The GPS satellites are monitored and tracked by ground support stations located worldwide. Uplink commands to each satellite provide corrections for ephemeris, frequency standard, and clock drift. Reference 12 (ICD-GPS-200) contains detailed information on the Space Subsystem.

3.2.1 Satellite Coverage. GPS signals from at least four satellites are typically needed to obtain an initial fix. In the contiguous United States, the current satellite constellation provides at least four satellites in view with favorable geometry at nearly all times. For purposes of flight safety support, it is seldom necessary to delay an operation to obtain suitable coverage. Coverage is also favorable in other areas of the world with the possible exception of polar areas. Worldwide coverage opens the possibility of developing a global range, wherein the vehicle receives and processes GPS signals and relays low bit rate position and velocity data via support satellites. Ranges can extend support capabilities and offer improved flexibility through this approach.

3.2.2 Satellite Signal Processing. Satellite signals are processed to extract pseudo range (from code track) and delta pseudo range (from phase or carrier track) measurements from each satellite. These measurements can be used to estimate the vehicle trajectory or state vector, i.e., position, velocity, and time.

3.2.2.1 Satellite Signal Codes/Characteristics. Satellite signals contain a coarse acquisition C/A code and a precision P(Y) code. The intent was to make the P code secure in times of national emergency to deny adversaries precision navigation information. However, C/A code signals processed in the carrier phase domain with commercial equipment can provide a high level of precision. The accuracy obtained simply from C/A code processing without error correction is often adequate for flight safety support. A properly designed commercial system can provide an accuracy of 100 meters in position and 0.3 meters per second in velocity at a 10-Hz sample rate with a latency at the processor output of less than 0.1 sec. Improved accuracy can be obtained with a secure receiver when its processor is provided with encryption keying. Improved accuracy can also be achieved without encryption keying by use of differential corrections. In this approach, errors that accrue in a stationary unit (or GPS reference receiver) at a surveyed location are applied to the mobile unit as corrections. The technique works well as long as the same set of satellite signals is processed in both the mobile and stationary GPS units.

3.2.2.2 Trajectory Measurement Accuracy Considerations. The achievable vehicle trajectory accuracy from GPS on a fix-by-fix basis depends on the Geometric Dilution of Precision (GDOP) and the User Equipment Ranging Error (UERE). GDOP refers to all geometric factors that degrade the accuracy of trajectory derived from an externally referenced measurement system. For GPS, common DOPs of interest include Position DOP (PDOP), Horizontal DOP (HDOP) and Vertical DOP (VDOP). These DOPs describe how specific geometries (satellites relative to GPS user) will cause the UERE to propagate. Note that the effective DOP is dependent on the geometry of the satellites in the user antenna field of view. Therefore, for flight vehicles not having spherical antenna coverage, it is prudent to model the antenna field of view in a 6 degree of freedom trajectory simulation together with the expected satellite constellation to develop DOPs. For flight safety support, it is further prudent for mission success to also run this simulation using the 3 sigma nominal trajectory tolerances to avoid surprises during actual mission flight. For some missions, simulations should also be performed at maximum vehicle turn rates. For spherical antenna coverage at near earth altitudes, mid-latitudes and a nominal 24 operational satellite constellation, a GDOP of 1.8-3.6 would be expected at most any time of year.

UERE refers to all factors contributing to GPS ranging errors (ephemeris, refraction, relative dynamics, receiver noise, etc.) and will thus vary depending on whether the user equipment is authorized, and if so, is tracking C/A or P(Y) code, and if tracking of the L1 and L2 frequencies is being done to minimize ionospheric refraction error. When combined, UERE times DOP provides a useful estimate of the expected trajectory accuracy. Tables 3-1 and 3-2 are included below to provide insight into the magnitude of UERE expected for GPS translator applications, specifically the RISPO sponsored Translated GPS Range Safety System (TGRS) translator/translator processor using authorized C/A code track.

Table 3-1. Pseudo-Range-Sum Measurement Error Budget		
Source	Error Budget (feet) RMS	
Satellite Segment ¹	Absolute	Differential (C/A)
Space Segment	15.7 ⁵	0.0
Control Segment	11.8 ⁵	0.5
User Segment-Translators		
Ionospheric Delay	21.0 ²	5.0 ²
Tropospheric Delay	1.0	1.0
Receiver Noise/Quant ³	8.0	8.0
Multipath ⁴	3.0	3.0
UERE (RMS-feet)	30.0	10.2

Notes:

1. It is assumed that SA effects are completely removed either by authorized use of decryption keys or by the differential corrections generated from differential corrections applied from an external source.

2. Ionospheric error is based on single frequency operation using the standard GPS ionospheric model for correction adapted for altitude to account for ionospheric penetration by exo-atmospheric vehicles. Error is reduced if real time translated L2 or L3 measurements are available.

The values reflect residual errors caused by decorrelation of the differential corrections for up to 250 miles separation between the translator equipped vehicle and the surveyed fixed site where the differentials were generated. It is assumed that the tropospheric corrections are removed from the differential corrections at the surveyed site and re-evaluated for the translator equipped vehicle location.

3. The values given are based on translated C/A code operation.

4. These values are nominal multipath induced errors. The actual errors may be significantly larger for brief periods particularly if the tracked vehicle is operating at low altitudes over water.

5. Accuracy as defined in the system specification for the NAVSTAR GPS, SS-GPS-300.

Table 3-2. Pseudo Range Rate Sum Measurement Error Budget	
Source	Error Budget (ft/sec RMS)
Space Segment	
Satellite Clock Noise	0.01
Propagation Gradient	0.03 ¹
User Segment	
Translator Phase Jitter	0.01
GTP Noise/Quant	0.03
Delta Pseudo Range Error	0.045
Equivalent dR/dT (50ms)	0.700

Notes:

1. This value reflects the tracking of a translator equipped vehicle which is below the ionosphere. It will increase during the traverse of the ionosphere.

2. This value reflects empirical performance for FFT derived measurements obtained during high jerk. The value stated is for 75 g/sec jerk.

3.3 Vehicle Subsystem

The Vehicle Subsystem consists of a GPS receive antenna, GPS receiver or translator modules, a downlink transmitter, and a downlink transmit antenna.

3.3.1 GPS Receive Antenna Configurations. There are several types of GPS receive antennas that are well suited to vehicle tracking. Some examples are: ring, single element, and summed element pairs (Figure 3-2). The correct choice depends on the vehicle, mission, flight safety requirements, flight profile, gain and coverage, and GPS module types.

An important factor to consider in choosing an appropriate antenna is the flight times when GPS data will be required. The determination must then be made as to vehicle attitude and attitude rates that may occur during each required support interval. If attitude is essentially constant or slowly changing during all required intervals, a single element antenna with less than hemispherical coverage may be adequate. If, on the other hand, vehicle attitude changes significantly during or between intervals, it may be necessary to use an antenna that provides nearly spherical coverage. An IMU can be used to circumvent the need for a spherical gain antenna by furnishing data during periods of GPS dropouts.

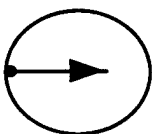
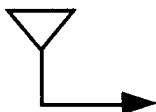
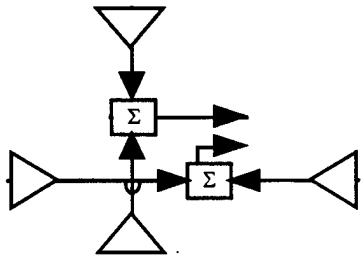
ANTENNA TYPE ATTRIBUTES	Ring	Single Element	Summed Element Pairs
			
COVERAGE	Nearly Spherical	Less Than Hemispherical	Nearly Spherical
MOMENT ARM ROLL AXIS	Minimal	Large	Large
COST	High	Very Low	Low
WEIGHT	lbs	oz	X oz

Figure 3-2. GPS Receive Antenna Configurations

3.3.2 Antenna Performance Considerations. As illustrated in Figure 3-2, the principal advantages of the ring antenna are nearly spherical coverage and minimal moment arm effects. These features increase the probability that a conventional GPS processor can acquire lock, retain lock, and provide adequate data. The principal disadvantages are development and purchase costs. The configuration is vehicle dependent and the antenna itself is comparatively large and heavy. Consequently, ring antennas are inappropriate for some vehicle classes. Single element antennas, on the other hand, are small, lightweight, and inexpensive. They can be readily adapted to all vehicles. However, coverage is limited and moment arm effects can be

large. Consequently, single element antennas are appropriate for some vehicle/mission scenarios, but inappropriate for others. An antenna array configuration that provides nearly spherical coverage with modest cost, size, and weight is the summed pair. Proper placement of each element on the vehicle assures that the signals received by one element will not interfere with the signals received by another element. The disadvantages of this configuration include large moment arm effects, and the need to receive and process signals from dual feeds. In most applications, the vehicle's center of rotation will differ from the phase center of the GPS antenna. The difference in locations is referred to as the moment arm. As the vehicle attitude changes, phase shifts will be introduced by the antenna system that are proportional to the length of the moment arm and the changes in vehicle attitude. Such phase shifts are called moment arm effects. These effects may cause errors in estimated velocity, and if attitude rates are sufficiently high, the GPS processor may lose lock entirely unless appropriate algorithms are used to compensate for the effects. In some configurations, concurrent use of an IMU can circumvent the need for such special purpose algorithms by providing state vector data during periods of GPS dropouts.

3.3.3 GPS Vehicle Modules. There are three basic types of GPS vehicle modules; analog translator; digital translator, and receiver. Refer to Figures 3-3a, 3-3b, and 3-3c.

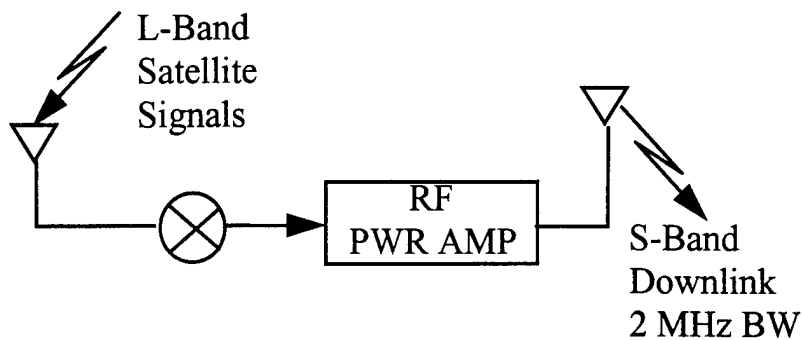


Figure 3-3a. Analog Translator

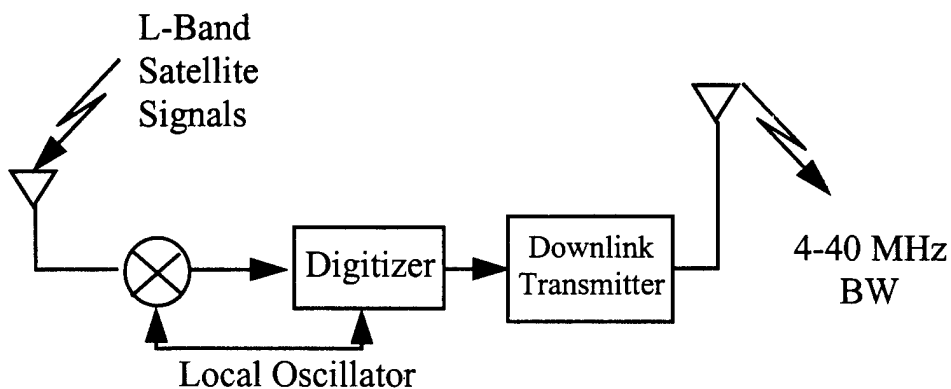


Figure 3-3b. Digital Translator

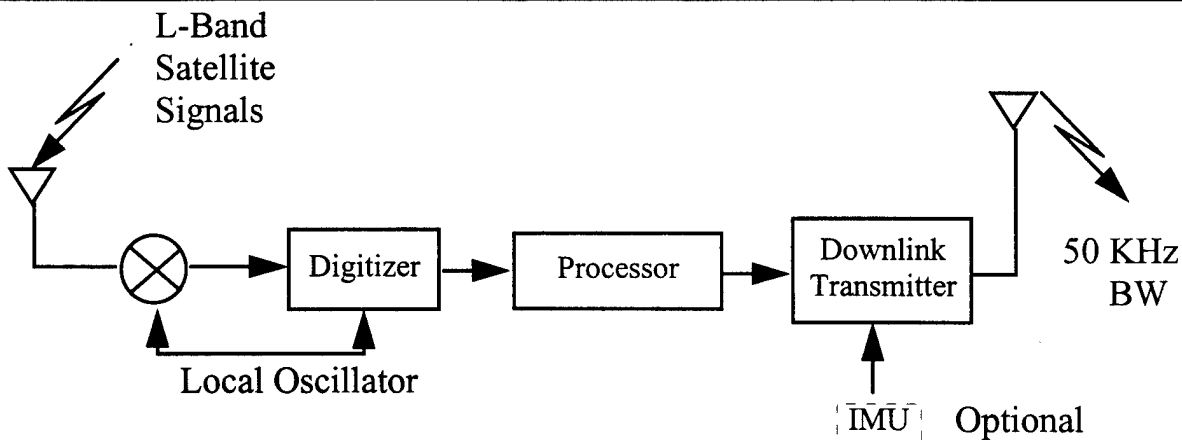


Figure 3-3c. Receiver/IMU Option

Table 3-3. GPS Vehicle Module Comparison		
ATTRIBUTES GPS MODULES	MULTIPLE ANTENNA INPUT CAPABILITY	MOMENT ARM, HIGH DYNAMIC RAPID LOCK/RELOCK CAPABILITY
TRANSLATOR	Yes	Yes
COTS RECEIVER	Some	Some
RECEIVER/IMU*	May Not Be Needed	Yes

* IMU can provide information during GPS dropouts and reacquisition

As mentioned earlier, receivers include the processor on the vehicle while translators use an off-board unit. Receivers transmit state vector (time, position, velocity, and health) via narrowband downlink, whereas translators relay all satellite signals in view via a wideband downlink. The GPS/IMU configuration transmits both the GPS receiver derived state vector and IMU measurements via a narrowband downlink. The IMU measurements provide a complete state vector including attitude, position, and velocity. The GPS data can be used to correct systematic errors associated with the IMU. The IMU errors accumulate slowly, so GPS updates are required infrequently.

Attributes of the basic types of GPS systems are summarized in Table 3-3. Subsystem elements must be properly matched to meet support requirements. If a summed pair antenna array is used, for example, the receiver or translator would have to provide inputs for dual feeds. If GPS data is required during vehicle maneuvers, the processor may require algorithms to correct for phase changes induced by the antennas (moment arm effects). If GPS data is required during periods of high vehicle dynamics (acceleration and jerk), the processor may require specialized algorithms to retain lock. In some applications it may be necessary for the processor to attain initial lock very quickly, and to reacquire lock almost instantaneously after an unlock.

The synergy obtained by coupling GPS and IMU systems can help provide some of the tracking attributes required and discussed above. Figure 3-4a depicts a loosely coupled receiver/IMU configuration. The receiver output is used by the navigation module to correct the raw IMU or INS (inertial navigation system) errors (drift, bias, scale factor). Independence of the two metric sources can be maintained. In this case, an optional IMU for flight safety would not be required if the user has provided raw INS measurements. In Figure 3-4b, a tightly coupled receiver/IMU configuration is depicted. When properly configured, independence of the two metric sources can also be maintained. The receiver measurements are used as in Fig 3-4a. In addition, the corrected IMU or INS and derived navigation information (time, position, velocity, attitude and attitude rates) can be used to aid GPS receiver reacquisition caused by GPS track dropouts, tracking loop aiding, satellite integrity checks, and lever arm corrections. These synergy benefits could permit the use of reduced performance modules (for GPS: antenna coverage, tracking loops; for IMU: drift, bias and scale factor) with a resulting decrease in module costs while still satisfying mission and flight safety metric requirements.

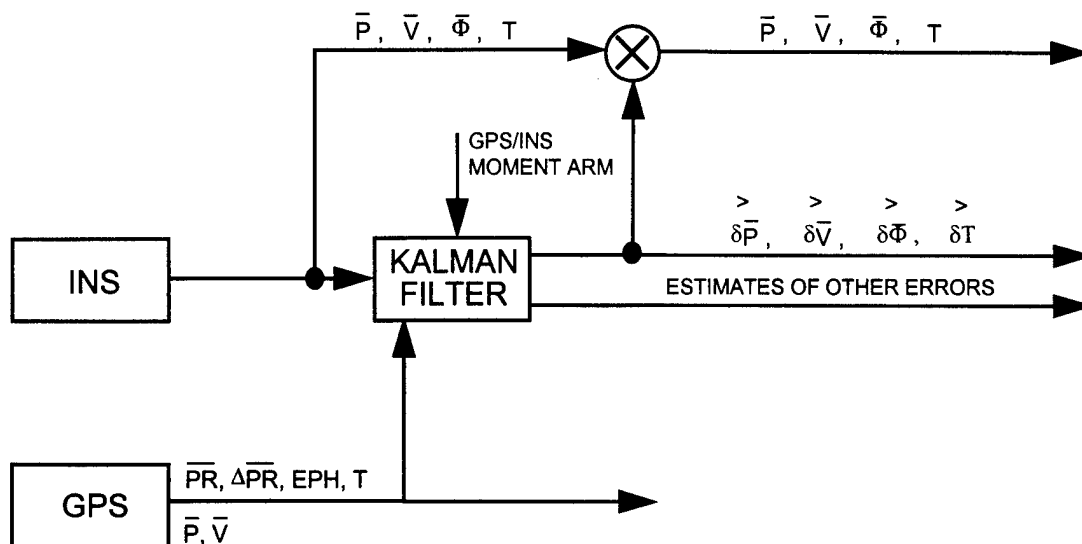


Figure 3-4a. Loosely Coupled Receiver/IMU

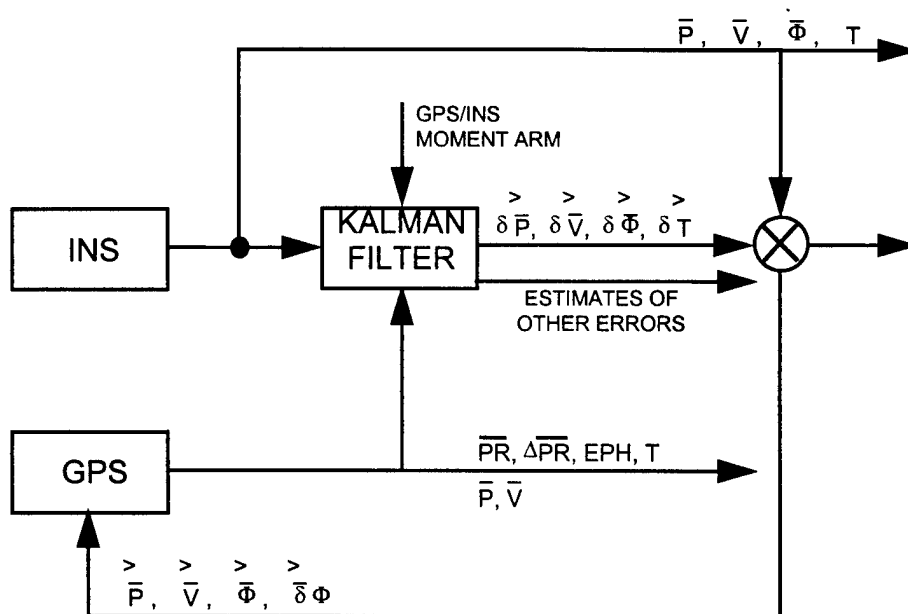


Figure 3-4b. Tightly Coupled Receiver/IMU

3.3.4 Downlink Transmitter. The GPS module used for flight safety interfaces with a radio frequency transmitter operating in an appropriate band. The transmitter RF power output must be adequate to provide reliable link closure with range ground stations. A translator system must radiate 10 to 20 times more power than receiver systems because of its wideband downlink.

3.3.5 Downlink Transmit Antenna. The GPS transmitter RF output can be coupled to the vehicle's telemetry antenna or to a dedicated antenna. The downlink antenna may also be used to relay signals from other vehicle transmitters that carry critical vehicle parameters and vehicle inertial guidance (IG) data. At some ranges the GPS vehicle modules (including the transmitter) must be independent of the vehicle telemetry modules, but the antenna and coupler are generally excluded from this requirement.

Coupling a low power, narrowband telemetry signal (such as GPS receiver or GPS/IMU signal) into the vehicle's antenna is straight forward. Coupling a higher power wideband translator signal, however, requires a more sophisticated design to guard against spurious noise and cross modulation products. The Trident vehicle coupler works well and could be adapted to other vehicle systems that use an analog translator. Coupler size, weight, and cost should not be overlooked. Data concerning the size, complexity, and cost of a coupler for the wideband digital translator signal were not available.

The downlink signal (the net product of coupling several transmitters to one antenna) must have very low L-band side bands if the L-band GPS receive antenna and the downlink antenna are located in close proximity on the vehicle. Side band levels can be lowered, as needed, by conventional techniques, but the size, weight, and complexity of modules that may be needed for a wideband digital translator signal should not be overlooked.

3.4 Range Subsystem

The range Subsystem includes receive/record sites, data transfer equipment, data processing centers and flight safety displays. For the purposes of this document, the Range Subsystem will not be discussed in detail. It is the ad hoc group's belief that integration of GPS support equipment into the ranges can be treated as business as usual, including installation of translator processing equipment.

3.4.1 Downlink Receive/Record. Range receive sites are typically equipped with receive antennas, banks of receivers, and recorders. Translator processors would typically be located at the receive sites to avoid relaying wideband signals. A translator processor includes a GPS reference receiver, an RF receiver, a demodulator, a recorder and a processor. The output data set of time, position, velocity, and health is in a selectable format suitable for data transfer via a standard low bit rate modem. Redundant range receive sites may be provided to assure adequate coverage throughout flight and to provide geographic diversity. Geographic diversity is required to assure that if a null in the vehicle's downlink transmit antenna pattern is directed toward one receive site, other nulls will not be simultaneously pointed toward alternate sites.

3.4.2 Data Transfer. Data transfer equipment is provided to route GPS receiver data or processed translator data to a central facility. The equipment may include conventional land lines, microwave, and/or fiber optics.

3.4.3 Data Processing. Processing of GPS data is typically accomplished at a central facility that provides best source select, data extraction, conversion to engineering units, and derived products such as present position and instantaneous impact point/predictions. Selected information is then routed to a real-time display area.

3.4.4 Real-Time Display. The real-time display area provides operations control personnel and the RSO with critical operational information required to assess vehicle flight safety status, both pre-mission and in-flight.



CHAPTER 4

GPS BASED METRIC SYSTEM RELIABILITY

As with other metric tracking sources, the question of system reliability is one that Flight Safety will be especially concerned with. This chapter describes the GPS reliability in terms of the Control, Space, and User Segments, including the Range Subsystem and includes discussions on how to mitigate potential problems. This chapter also briefly discusses jamming and spoofing considerations.

4.1 Space Segment

4.1.1 Satellite Reliability. Since the reliability of the Space Segment is relatively high, satellite related failures are not expected to be significant problems for flight safety. A study conducted by Aerospace Corporation (reference 5) in which data was compiled from April 1992 to November 1993, counted 23 events in which the ranging error of an on-orbit GPS satellite exceeded 100 meters. From this data, Aerospace Corporation was able to estimate satellite reliability. "The probability that a given satellite, which is nominal and healthy at a given time, will not exhibit range error in excess of 100 meters at any time during the following one-hour interval" is approximately 0.99992. The most serious anomalies that have been observed by the 2D Space Operations Squadron are clock frequency ramps. The occurrence of the ramps is generally associated with satellite clock failure, rendering the satellite signal useless for navigation until the satellite is switched to a backup clock. In some cases, the magnitude of the frequency ramp is so large any receiver that is tracking the link upon which the ramp event occurred will immediately lose lock and not be able to reacquire the signal.

Mitigation -

- Use of either a GPS reference receiver or downlinking of the raw data to monitor the integrity of the individual satellites being tracked. It may be further necessary to use real-time measurements from these reference receivers to correct or compensate the navigation solutions generated by the flight vehicle's GPS metric system processor.
- Receiver Autonomous Integrity Monitor (RAIM) refers to algorithms designed to detect the presence of a satellite anomaly within a particular group of satellites, identify the offending satellite, and subsequently eliminate use of this satellite from the ongoing navigation process. The RAIM, as conceived within the civil aviation community, is not directly applicable for flight safety because of its relatively slow (order of minutes) response time since the input is unauthorized user quality measurements. For authorized users, the increased accuracy of GPS enhances the ability to perform integrity monitoring. The basic RAIM methodology takes measurements from five satellites to detect an anomaly, and measurements from six to isolate and eliminate the anomaly. For six satellites to

be sufficient, it is necessary that the anomaly be limited to a single satellite and that the six unique navigation solutions, which are formed by deleting one satellite at a time, clearly distinguish one solution as being inconsistent with the other five unique solutions.

4.2 Control Segment

4.2.1 Periodic Maintenance. GPS satellites are routinely set unhealthy twice a year for scheduled maintenance. Also, a great proportion of satellite anomalies occur when the satellite emerges from the Earth's shadow during the "eclipsing" season. For each satellite, the eclipsing season is of approximately 40 days duration each year, and each eclipse varies from a few minutes to slightly less than one hour duration.

Mitigation -

- Since eclipsing is a predictable phenomenon and maintenance is scheduled, users can enhance navigation integrity by avoiding the use of satellites that are in eclipse or have not had an upload since their last eclipse.

4.2.2 Ranging Error Anomaly. A criterion used by the 2D Space Operations Squadron to declare a satellite anomaly is "Ranging Error Exceeds 12 Meters." Such ranging errors typically (although not always) occur either in increments of 30 meters in the P code or as jumps in clock frequency or phase. When anomalies affecting ranging errors are detected at any one of the world-wide network of GPS monitor stations, the 2D Space Operations Squadron uploads a message declaring the "unhealthy" status of the satellite in question. In 1997, the time delay between the occurrence of a satellite anomaly and setting the satellite to unhealthy status can be on the order of several hours or longer.

Mitigation -

- The time delay associated with detecting the anomaly and setting the unhealthy status will be lowered when a full constellation of the next generation satellites having cross-link communication capability are on-orbit.

4.3 User Segment - Vehicle Subsystem

4.3.1 Satellite-to-Vehicle RF Link. As discussed in Chapter 3, paragraph 3.3.1, if the vehicle's GPS receive antenna coverage is not spherical it may not be possible to receive an adequate set of satellite signal measurements at all vehicle attitudes.

Mitigation -

- Proper antenna design considerations such as use of a low cost, lightweight multi-element antenna configuration that will provide nearly spherical coverage.
- Consideration of moment arm effects.

4.3.2 Vehicle Modules. Analog and digital translators, as well as receivers, are electronic devices that are subject to all failure modes typical of such devices. High vehicle dynamics (such as acceleration and jerk) and antenna moment arm effects can cause significant errors when conventional GPS processors are used. In the extreme case, the GPS processor may lose lock entirely.

Mitigation -

- Proper design considerations and testing by the user.
- Today's translator processors include algorithms that provide useful data even during intervals of high vehicle dynamics. GPS receiver systems have circumvented the need for inclusion of such algorithms by including an IMU as a part of the system. The IMU continues to provide data during intervals of high dynamics, and the GPS data obtained during intervals of low dynamics is used to correct slowly accumulating IMU errors.
- Pre-mission simulations to identify potential dropout intervals due to nominal and/or worst case dynamics/environments.
- Ground processing of raw measurements. The flight safety solution could be generated on the ground using telemetered GPS measurements from an on-board receiver which have been checked for integrity in real-time with reference receiver data. This alternative could potentially achieve 100 percent integrity for each GPS satellite measurement being used in the flight safety trajectory solution.

4.3.3 Vehicle-to-Range RF Link. Vehicle telemetry antennas seldom provide spherical coverage. Most have deep nulls in several directions. Consequently, it is not possible to provide a useable vehicle-to-ground link with a single receive site for all vehicle attitudes.

Mitigation -

- Ranges circumvent this problem by use of geographically separated receiving sites located to provide coverage throughout flight and to provide spatial diversity. Spatial diversity is needed to ensure that a good link is established to at least one site when a vehicle antenna null is directed at another. In some cases, vehicle events such as staging will cause all telemetry links to fade simultaneously. Such problems have historically been of short duration.

- Pre-mission simulations, together with range end-to-end testing, can be used to identify potential dropout intervals.

4.4 User Segment - Range Subsystem

Range Downlink. Range subsystems include antenna pedestals, telemetry receivers (or other downlink equipment), and data transfer, data processing and display equipment. This equipment is subject to a variety of failure mechanisms as documented in range databases. Seldom will the reliability of a single support string (receive antenna through display) meet requirements for range readiness and mission success. Reference 6 indicates that the use of telemetry assets for GPS support provides the opportunity to improve reliability and reduce cost, as compared to a radar based support configuration.

Mitigation -

- As discussed earlier, reliability is typically achieved through redundancy of range equipment, processing, and displays.
- Pre-mission simulations, together with range end-to-end testing can be used to identify potential dropout intervals or problems with range support configuration.

4.5 Other Considerations: Jamming and Spoofing

GPS systems are susceptible to interference from radio frequency (RF) transmissions. Unintentional interference from high powered terrestrial RF sources can be identified and controlled by the range. Historically, unintentional interference has not been a problem when GPS equipped vehicles are airborne. There are two ways of intentionally interfering with GPS signals: jamming and spoofing.

- Jamming is the intentional transmission of RF signals to restrict access to the GPS constellation. This would typically result in a complete loss of data and obviously could be a major problem for flight safety.
- Spoofing is the intentional transmission of errors in the GPS satellite signals or transmission of GPS signals from bogus satellites. This would result in degraded data and may or may not be a problem for flight safety depending on the amount of data degradation.

Though the ad hoc group does not believe jamming and spoofing to be a prevalent problem, there are several ways to mitigate the effects on flight safety as discussed below.

4.5.1 Jamming Considerations. A potential source of jamming is Electronic Warfare (EW) testing. The majority of EW tests can be conducted within the confines of a laboratory environment. When EW operations cannot be contained locally, they are conducted under very carefully controlled and coordinated conditions. Each EW tester is required to request a minimum of 60 days in advance at the national level for authorization to radiate. Included with

this request are the characteristics of the specific test (time, location, radiated power, antenna gain / directionality / polarization, and operating characteristics, etc.). Affected agencies such as Range Control, the Local Area Frequency Coordinator, and the Federal Aviation Administration (FAA) are notified in advance. Unless it is critical to radiate during daylight hours, tests are conducted only during nighttime hours. Jamming can also be detected by frequency surveillance. Each range generally monitors critical frequencies during test operations to rapidly detect and eliminate potential sources of interference in the pre-launch countdown.

Tactical aircraft or missile systems that rely on GPS for guidance and navigation generally utilize methodologies to minimize the affects of EW. Methodologies exist to electronically control vehicle antenna patterns and thereby null out detected sources of interference. In addition, the intentional use of jamming during tests of tactical systems will be known in advance so that alternative tracking technologies can be used if the flight safety GPS track is expected to be affected. Ground GPS systems often have additional means available such as shielding or horizon masking to screen sources of terrestrial interference.

4.5.2 Spoofing Considerations. Spoofing introduced on GPS satellite signals can be neutralized by use of P(Y) codes or by the use of a GPS reference receiver tracking common satellite signals to detect a spoof.

CHAPTER 5

MISSION DESCRIPTIONS AND LESSONS LEARNED

Use of GPS to provide metric data has expanded to many Department of Defense (DoD) programs. Rapidly developing technology is spawning new applications at an accelerating rate. Evidence of this trend is demonstrated by the number and diversity of GPS applications at the ranges. This Chapter describes some of these applications and lessons learned from each application, as well as a summary of general lessons learned.

(ED. NOTE: At request of the ad hoc group, the information that follows was not edited or altered in any way from the original material provided to the Secretariat.)

5.1 Mission Descriptions

The ad hoc group survey (Reference 2) identified several generic vehicle classes that have used or are using GPS. Some examples are discussed below, including a basic description of the program and GPS configuration, as well as a list of lessons learned from that particular program. This list is only a small subset of GPS applications that the ad hoc group was able to document.

- 5.1.1 Spacelift Vehicle (SLV) - Pegasus
- 5.1.2 Reusable Launch Vehicle (RLV) - X34
- 5.1.3 Ballistic Missile (BM) - Multi-Service Launch System (MSLS)
- 5.1.4 Ballistic Missile, Targets (BMT) - Storm Missile Technology Demonstration Program
- 5.1.5 Ballistic Missile, Targets (BMT) - Theater Missile Defense Hera Target
- 5.1.6 Surface to Surface Missile (SAS) - Army Tactical Missile System (ATACMS)
- 5.1.7 Air to Surface Missile (ASM) - Standoff Land Attack Missile (SLAM)
- 5.1.8 Air to Air Missile (AAM) - Advanced Medium Range Air to Air Missile (AMRAAM)
- 5.1.9 Ground Collision Avoidance System Testing
- 5.1.10 Unmanned Air Vehicles (UAVs) - Medium Range Unmanned Aerial Vehicle (MR UAV), Miniature Air Launched Decoy (MALD), and Predator
- 5.1.11 Smart Munitions (SM) - Miniaturized Munition Technology Demonstration Program
- 5.1.12 Ordnance Fusing - Reentry Body Impact Fuze Flight (RBIFF)
- 5.1.13 Artillery - Hardened Subminiature Telemetry and Sensor System (HSTSS)
- 5.1.14 Artillery - GPS Auto-Registration System
- 5.1.15 Artillery - EX-171 Extended Range Guided Munition (ERGM)

5.1.1 Spacelift Vehicle (SLV) - Pegasus. The Pegasus system is a three-stage, solid propellant expendable launch vehicle that is inertially guided and 3-axis stabilized. Its capabilities vary depending on the performance option package it may be flying. In the XL configuration, Pegasus is capable of placing approximately 485 lb payload into a 400-nm circular polar orbit. With the Hydrazine Auxiliary Propulsion System (HAPS) option, the Pegasus can support a 700 lb payload to the same orbit. The vehicle is mounted and carried on a carrier aircraft and released from an altitude of approximately 39,000 ft. On the 25 April 1993 Pegasus flight from

Vandenberg AFB, Orbital Sciences Corporation included a Trimble GPS receiver. The 30th SW at VAFB collected receiver output telemetry and performed a post mission evaluation to compare GPS usefulness for flight safety with traditional metric tracking sources (radar, TMIG). Review of the GPS receiver telemetry output indicated that the receiver was capable of providing state vector estimates which are more accurate than required for most flight safety support situations. Questions concerning reliability, data link delays and data rates were not considered because this was a "launch of opportunity" to evaluate a GPS receiver.

Lessons Learned: Inherent accuracy of GPS appears adequate for flight safety. COTS (commercial off-the-shelf) receivers will not necessarily satisfy safety requirements for a metric tracking source (data rates, reliability, etc.).

5.1.2 Reusable Launch Vehicle (RLV) - X-34: The X-34 is the first of a new class of Reusable Launch Vehicles (RLV) being developed for NASA by the Orbital Sciences Corporation. This vehicle will serve as a test bed for emerging new spacelift technologies designed to lead to low-cost, rapid-turnaround access to space in the next century. An incremental series of tests are planned beginning in Nov 98. Later tests of this vehicle will include flights at altitudes up to 250,000 feet and velocities up to Mach 8. Initial tests include air launching over WSMR from an L-1011 aircraft operating at 38,000 ft altitude and 700 ft/sec velocity. Tests include both powered and unpowered flight. In non-powered scenarios, following release, the X-34 will perform a simulated emergency landing into a nearby site. In powered flight, the X-34 will climb to a designated altitude and velocity. Vehicle powered flight begins shortly after release from the L-1011 lasting for a specified period with the remainder of flight and landing under energy managed glide conditions. Thrust is provided by a LOX/RP-1 single engine also under development by NASA. In the event of no engine ignition after release from the L-1011, an emergency landing at an established landing site is planned. The X-34 vehicle receives steering commands derived from information provided by an on-board autonomous GPS aided inertial guidance and control system. This system also receives real-time inputs from the vehicle Flush Air Data System (FADS). This control system will execute the autonomous, "deadstick" (Space Shuttle) landing on the Holloman AFB full scale drone runway. Vehicle guidance will be augmented for a precision landing by means of both a radar altimeter and differential GPS uplink. Later testing at multiple test Ranges, including the Eastern Test Range, are planned.

It is planned that GPS will provide a primary flight safety real-time track. In addition, differential GPS will be required for safe precision landing. A Litton LN-100 strapdown INS with a Rockwell Collins GEM III receiver will perform primary guidance and control. An onboard Loral transceiver and embedded GPS receiver provide differential updates to this system during landing. These systems will be qualified to Mil Std 1540 and 810 (Aircraft) standards as applicable. It is planned that an L-1011 rerad system will ensure X-34 GPS acquisition / initialization prior to deployment. Use will be made of patch antennas for L- and S-band signals.

Lessons Learned: The first flight is currently planned for Mar 1999.

5.1.3 Ballistic Missile (BM) - Multi-Service Launch System (MSLS): The Multi Service Launch System (MSLS) flew a modified HDIS GPS receiver on their first three flights out of Vandenberg AFB. The system was implemented to use two patch antennas, 110 degrees apart on

the roll axis, with each antenna providing an 80 degree radius field-of-view. The HDIS system is a P(Y) code, five channel GPS receiver (four tracking, one acquiring) and weighs approximately 20 lbs. It was loosely coupled with an INU to support the navigation function in the MSLS application. Although using an existing system reduced development costs, it left analysts with little information for performance evaluation. Due to security constraints, the unencrypted ranging data (pseudo range and delta pseudo range) telemetered from the receiver was not allowed to be downlinked. Had a C/A code receiver or a telemetry encryption device been used, these ranging data would have provided invaluable information on this patch antenna interface configuration. The firmware in the HDIS calculates which four satellites in the antenna field-of-view provide the best PDOP based on user provided antenna patterns and vehicle attitude. The INU provides vehicle attitude to the HDIS firmware, however, the receiver updates the satellite constellation (positions) every 30 seconds. Thus the satellites defined as in the field-of-view are updated every 30 seconds. The problem with this implementation starts when the vehicle rotates and the selected satellites are no longer in the antenna field-of-view from either of the two patch antennas, or satellites that could provide a good PDOP come into view are not selected. The loss of sight, and thus signal to the receiver limited the availability of meaningful GPS-based position and velocity updates for INU error correction.

Lessons Learned:

- The user must understand the receiver design when applying an existing design to a new application.
- Performance evaluation analysis of GPS related systems is severely limited when pseudo range and delta pseudo range measurements are not available.
- A patch antenna system that limits the field-of-view also limits satellite availability therefore causing periods of questionable position and velocity data especially during changes in vehicle attitude.
- Satellite constellation updates should be performed at a rate that is compatible with rotation rates and antenna field-of-view.

5.1.4.a. Ballistic Missile Targets (BMT) - Storm Missile Technology Demonstration (MTD)

Flight Test - MTD-1: The Storm MTD-1 vehicle was successfully launched from WSMR on 16 Aug 1995. Project test objectives included demonstration of an on-board tightly coupled Differential Global Positioning System (DGPS) and IMU solution in real-time. This was achieved by using raw pseudorange data from a Trimble TANS II GPS receiver and merging it with data from the vehicle inertial system. Differential GPS corrections were generated using a ground-based Trimble Pathfinder Community Base Station and uplinked to a receiver on-board the missile. The TANS receiver-derived solution, the merged DGPS/IMU solution, and the IMU solution were used to generate an Instantaneous Impact Prediction (IIP) in real-time. The IIP is used by the Safety Officer as the primary indicator of vehicle performance. Only the IMU IIP was monitored by the Safety Officer. The DGPS/IMU IIP was derived as part of the assessment of GPS as a range safety tracking source. A secondary Project objective was to evaluate an on-board autonomous flight termination algorithm, using the merged DGPS/IMU solution to

generate a vacuum IIP on-board the missile. The on-board vacuum IIP was telemetered to the ground and directly displayed in real-time, alongside the vacuum IIP generated by the Range, based on the same merged DGPS/IMU solution. In addition, the Range was able to "piggyback" on this flight test by integrating an analog GPS translator which also provided a real-time ground-based GPS solution. The Range Applications Joint Program Office (RAJPO) provided the Ballistic Missile Translator (BMT). The Range also generated an IIP from the BMT data.

The post mission analysis compared the TANS receiver-derived solution, merged DGPS/IMU solution, BMT solution, and the IMU solution to a radar best estimate of trajectory solution. The merged DGPS/IMU was by far the best data source and was the basis for an excellent IIP in real-time. The position and velocity errors were relatively small, with the GPS contributing significantly to reducing the drift normally seen in IMU systems. As the second best data source, the BMT solution also resulted in an excellent IIP, despite the fact that it was not differentially corrected in real-time. The Storm IMU is currently monitored as a real-time safety data source by the Safety Officer. The IMU was the third best data source and as expected the largest errors were in the east direction due to IMU drift. Though the TANS receiver performance exceeded Project objectives, the TANS receiver-derived solution was considered to be unusable as a flight safety data source. This was primarily due to the receiver operational mode and the delays in transmitting the receiver solution. The autonomous on-board flight termination algorithm performed as expected, though the on-board vacuum IIP was found to lag the Range-derived IIP solution. This was later attributed to differences in earth models.

Lessons Learned:

- Vehicle GPS/IMU guidance and navigation systems have many benefits to user over IMU only systems. They also have potential to be used as sources of real-time flight safety data.
- The on-board IIP was developed, in part, to guide the vehicle to a space point several thousand kilometers above the ground. So, the IIP was not generated for ground impact level where the Safety Officer would be most concerned. Conflicts could exist in satisfying both guidance and safety objectives with the same system. However, an on-board flight termination algorithm based on GPS as a source of truth data has merit and should be further investigated.
- Data transmission/latency times must be minimized if the GPS data is to be used a safety data source. The TANS II receiver solution was not usable as a safety data source, primarily due to the delays in transmitting the data.
- Though GPS simulation data was provided to the Range, it was only static data. Dynamic simulated data would have provided a better means of validating GPS performance, as well as Range processing and display software.
- This was the Range's first experience with the Military-off-the-Shelf (MOTS) Ballistic Missile Translator and the ground processing system. The system was not very user friendly and required special training to operate. In addition, the proprietary nature of the system and problems with encryption of the data prevented the best analysis of data.

- Early coordination with the Project and contractor is essential to ensure that safety requirements can be incorporated early in the design and development stages without impacting the program.

5.1.4.b. Ballistic Missile Targets (BMT) - Storm Missile Technology Demonstration (MTD) Flight Test - MTD-2: The Storm MTD-2 flight test took place at WSMR in January of 1997. The MTD-2 vehicle was a single stage SR-19 motor with a Pershing II Reentry Vehicle (RV). The MTD-2 vehicle carried a variety of GPS systems. The reentry vehicle carried a merged differentially corrected DGPS/IMU system (TANS II GPS receiver and Pershing inertial gimbal system). This was the same DGPS/IMU system which was successfully flight tested on MTD-1. For this flight, the DGPS/IMU was actively being used for guidance and navigation. The merged DGPS /IMU solution was also an input to the on-board autonomous flight termination algorithm. Several changes had been made to the algorithm, including destruct criteria based on vehicle performance. As with MTD-1, the on-board algorithm was flown strictly in passive mode. The reentry vehicle also contained a small, low cost commercial avionics Ashtech G-12 GPS receiver, with special high dynamics software suited to withstand the expected vehicle dynamics. The receiver was ruggedized and repackaged by Orbital Sciences for flight. The Range also processed raw pseudorange and range rate information from the Ashtech receiver and generated (post-mission) a ground based solution. The Range provided a standard Ashtech receiver that was used as a reference receiver. The Range generated Instantaneous Impact Predictions (IIPs) from all these data sources. The booster carried two merged GPS/IMU systems (Honeywell H-764G and Litton LN 100LG), both using strapdown inertial systems. Data from these two systems was not displayed in real-time by the Range. All GPS systems utilized ring type (wrap around) antennas. One antenna was located on the RV and the other on the ballast module between the interstage and the payload. Both the reentry vehicle and the booster contained C-band transponders.

A vehicle control problem occurred during boosted flight resulting in the vehicle tumbling for over 30 seconds. It was eventually terminated by the Flight Safety Officer. Because of the extreme environments during the failure, the data gathered during the test was extremely useful. The DGPS/IMU solution which utilized a gimbal type inertial system, exceeded the systems angular rates approximately 10 seconds after the vehicle begin to tumble and resulted in erroneous data. The TANS II GPS receiver never lost track during the tumbling. The IMU only solution was being used by flight safety as a data source, and was being validated with radar. When the IMU solution diverged and no longer agreed with the radar data, it was no longer used as a safety tracking source. The Ashtech receiver lost satellite lock for a few seconds when the vehicle first begin to tumble, but reacquired within 5 seconds and provided good data through the end of flight. The Ashtech ground based solution derived by WSMR, though not performed in real-time, also provided a good solution through the end of flight and was able to provide a solution through the vehicle tumble period. The Range used the other Ashtech reference receiver to provide differential corrections to the Ashtech solution, resulting in high quality data. Both the Litton and Honeywell systems which utilize strapdown IMU systems tracked during the vehicle tumbling and provided data through the end of flight. The GPS system in the Honeywell unit experienced problems with IMU aiding and reacquisition during the initial tumble period.

Lessons Learned:

- Despite the vehicle control failure and the very dynamic environments experienced during the flight, all GPS systems performed well in providing useable tracking information.
- Use of a low cost, commercial off the shelf GPS receiver with software modifications for anticipated flight environments and properly packaged has potential as a safety data source. This system provided not only an on-board receiver output, but also served the function of a translator by downlinking pseudorange and range rate information for ground processing. This configuration offers multiple options as a flight safety data source.
- Despite the 5 second dropout during the initial tumble period, the Ashtech receiver reacquired lock very quickly. This dropout time would likely have been acceptable given the vehicle capabilities which would have not exceeded the Range boundaries during this time period.
- Independent processing of raw pseudorange and range rate data by the Range provided another solution, that due to the special ground processing was able to carry through the data dropout.
- Merged GPS systems which have strapdown inertial systems rather than the gimbal type systems had an advantage in tracking through the extreme vehicle dynamics.
- The Ashtech receiver solution was not properly processed by the Range in real-time, resulting in erroneous display, even though the receiver solution was good. A dynamic simulation tape of the Ashtech GPS data would have identified the Range processing errors before the mission. This only serves to emphasize the need for GPS dynamic simulation information prior to launch.

5.1.5 Ballistic Missile Targets (BMT) - Theater Missile Defense Hera Target: The Hera target vehicle is built by Coleman Aerospace Company under the TMD Targets contract for the U.S. Army Space and Missile Defense Command. The ninth flight of the Hera is currently scheduled for December 97 from Ft. Wingate, NM to White Sands Missile Range (WSMR). Impact range is approximately 215 miles. The configuration for this flight demonstration will be a Block IIB target, which consist of an SR-19 first stage, M-57 second stage, and a threat representative reentry vehicle. One of the objectives of this flight is to demonstrate the operation of a GPS/INS-based navigation and tracking system in a suborbital launch vehicle environment. This advanced vehicle avionics (AVA) package includes an M-MIGITS integrated GPS/INS and a DY-4 68040 processor in a Radstone VME chassis. The M-MIGITS is a tightly coupled system which utilizes a digital quartz IMU from Boeing Autonetics and a Rockwell GNP-10 navigation processor with 10 channel receiver. The off-the-shelf GPS/INS and processor were integrated with a telemetry encoder, interface electronics and power distribution system which were designed and developed by Coleman Aerospace. The GPS antenna system includes 3 patch antennas. Much of the GPS data, including raw measurements, merged GPS/INS navigation data, and status, will be telemetered to the ground for post-mission processing and minimal real-time display at the Range Control Center at WSMR. For this flight demonstration, the GPS/INS

system is separate from the primary vehicle guidance and navigation system, which is based on a re-used Pershing II inertial platform and electronics. It is anticipated that the AVA will be used as the primary guidance and navigation system for a mission in 3rd Qtr 98, and will further be used to support range safety tracking for Wake Island/Kwajalein missions beginning in 4th Qtr 98.

Lessons Learned: Post-mission evaluation will be conducted by Coleman Aerospace and they have agreed to brief the ad hoc group on the results of the mission and share any data and lessons learned.

5.1.6 Surface to Air Missile (SAM) - Army Tactical Missile System (ATACMS): The Army Tactical Missile System (ATACMS) tactical ballistic missile developed for the Army by the Lockheed Martin Vought Systems. The vehicle is a solid propellant, single stage, surface to surface, inertial guided missile. The missile is designed as a deep strike, anti-personnel/anti-armor weapon system. Steering of the ATACMS is accomplished by means of fins and therefore retains the ability, albeit limited by atmospheric density over portion of flight, to steer throughout flight. The payload is designed to carry bomblets or smart submunitions. The missile is launched from within a Missile Launch Pod Assembly (canister) from a mobile launcher. GPS was added to the ATACMS missile to meet stringent terminal flight delivery accuracy at increased ranges.

Initial flights utilized the Rockwell GEM I receiver. The IMU is a strapdown ring laser gyro system. Raw GPS receiver and IMU outputs are telemetered separately to the ground thus providing independent data sources for flight safety. GPS inputs are ignored in the onboard navigation solution when unavailable or when significant differences exist between the strapdown IMU and GPS. The vehicle has routinely demonstrated a capability for autonomous flight without the aid of the onboard GPS, the result being a possible degradation of delivery precision at extended range. A preferred flight safety real-time data source is already provided by the normally excellent raw IMU position and velocity information when verified with radar data to monitor vehicle performance in real-time. The GPS antenna system is a 2 element array designed to reduce the effects of temperature, mutual coupling, and enhance null mode performance. Launches occur from within a canister which is opaque to radio frequency energy. To aid in acquisition, a Rockwell Collins GEM III located in the mobile launcher, is used to initialize the vehicle EGR prior to launch. The mobile system is a 5 channel, L1- L2, P-Code receiver capable of providing 1 second updates and a warm start time to first fix of 10 seconds.

The missile has been launched from several locations both on and off Range at WSMR. Range tracking radars, in conjunction with telemetered vehicle status and inertial data are normally used to provide continuous metric data throughout the trajectory. In addition, at least one skin tracking radar is required throughout the trajectory. Since other means of flight safety track were available, the user did not specifically design the GPS to be used as a safety data source. WSMR used this opportunity to evaluate the use of GPS to gain lessons learned for flight safety. Since traditional data tracking sources have been available, full use of the GPS has not been implemented for real-time flight safety track.

Lessons Learned: The ATACMS tests were the first WSMR Flight Safety experience with GPS on a vehicle with missile dynamics. Many useful Flight Safety lessons were learned from the ATACMS early GPS flights. Only raw GPS receiver information was evaluated as a data source for flight safety in these tests.

- The fact that GPS inputs are ignored in the combined onboard GPS-IMU solution used for vehicle guidance under certain circumstances, raises concerns that the use of the combined GPS-IMU output could, at times, be unverified IMU only information. This may preclude this output from use as a stand alone source of data. However, the GPS receiver output and IMU only output in this loosely coupled configuration could possibly be considered as independent data sources.
- Based on test scenario and this vehicle's dynamics after burnout, in spite of the 1 Hz data sample rate, GPS receiver information could have been used as a flight safety tracking source after motor burnout.
- The sudden loss of on-board telemetered information on one flight test causing immediate loss of GPS tracking information is unacceptable from a flight safety mission success perspective and the addition of other tracking sources such as a separate GPS based or radar systems is warranted.
- Moving data, whether obtained from a previous flight or simulated, is important in Range interface validation prior to vehicle launch. For a coupled GPS-IMU system, both the GPS and IMU systems should be exercised separately and together to fully verify integrated system and Range display performance.
- Data validation methodologies may be needed in some missile configurations which not only check GPS health status but also detect the absence of current / moving data (i.e., preclude the display use of old data).
- If the intended use of the GPS system includes flight safety tracking, an early-on Range input to system design is important.

5.1.7 Air to Surface Missile (ASM) - Standoff Land Attack Missile (SLAM): The AGM-84E Standoff Land Attack Missile (SLAM) is an air-to-surface missile employed by the U.S. Navy. It navigates using a modified AGM-84 Harpoon Attitude Reference Assembly (ARA) and receives aiding from a single channel GPS receiver. It uses two Right Hand Circular Polarized L-band antennas (Wide and Narrow Beams). SLAM test flights are conducted at the Naval Air Warfare Center Weapons Divisions (NAWCWPNS) Sea Test Range off the coast of Point Mugu, CA and White Sands Missile Range (WSMR) in New Mexico. Missile telemetry data, which included GPS navigation data, as well as tracking radar data are used for range safety purposes at these Ranges.

Lessons Learned: GPS position is compared to tracking-radar position to verify NAV. Lengthy time-to-first fix makes inertial (telemetry) position unusable during initial portion of flight. The

second generation of the SLAM called SLAM-Expanded Response (ER) will use a five-channel GPS receiver which will improve its GPS portion.

5.1.8 Air to Air Missile (AAM) - Advanced Medium Range Air-to-Air Missile (AMRAAM)

The AMRAAM, or AIM-120, is a missile system intended to replace the Sparrow AIM-7 for interception of hostile aircraft beyond visual range - up to 30 miles - in a "Fire and Forget" mode. It is currently in use on many models of USAF, Navy and NATO aircraft, and is deployed in the US, UK, Germany, S. Korea and Turkey. The Mach 4 missile is guided by a strapdown Northrop inertial reference unit (IRU) with autopilot, accepts midcourse correction from the pilot by datalink, and accomplishes terminal guidance with an X-band pulse-Doppler radar seeker. It is produced by Hughes, with Raytheon as a second source.

GPS is planned to be added to the Eglin Range and White Sands Missile Range test vehicles in the year 2000 timeframe, as the primary range safety metric data source. The unit planned for use is the Translated GPS Range System (TGRS) developed by Interstate Electronics Corporation for the USAF Range Instrumentation Systems Program Office (RISPO). To accommodate the TGRS, these ranges will be equipped with the GPS Translator Processor (GTP) equipment in the interim. This will be the first experience of AMRAAM with GPS.

Lessons Learned: Since the use of GPS on AMRAAM is still a future development, no lessons learned can be gleaned at this time.

5.1.9 Ground Collision Avoidance System Testing (GCAS): The GCAS system was tested at the Air Force Flight Test Center (AFFTC) at Edwards AFB, CA. The test team used a modified Advanced Fighter Technology Integration (AFTI) F-16 aircraft as the test bed for this test. The basic concept of GCAS was for the aircraft to recover itself if the pilot was impaired or unconscious. The testing was accomplished North of the main base at an uninhabited desert mountain peak and consisted of the pilot intentionally flying the aircraft into the side of the mountain and have the aircraft recover without inputs from the pilot. This was obviously a hazardous test with a fighter aircraft flying into the ground, sometimes inverted, and only the onboard software and the aircraft's computers and sensors to save the pilot.

As a risk reduction procedure it was determined that an external form of real-time Time Space Positioning Information (TSPI) was required. Due to the distance from the radar sites and the speed and altitude of the aircraft, radars were unable to provide this information. To satisfy the safety requirements, a Range Applications Joint Program Office (RAJPO) Advanced Range Data System (ARDS) pod was attached to the aircraft. The ARDS pod sends GPS/IRU to the control room via a dedicated data link. This information was displayed on the Test Conductor's display and was used to make the call to pull out if the on-board system did not function properly.

Lessons Learned: The instrumentation radar, even though the aircraft had a beacon, could not keep the track as the aircraft approached the ground due to multi-path problems. The ARDS pod with the onboard IRU kept track through the maneuvers of the aircraft. Also, the accuracy of the ARDS TSPI was not degraded as the aircraft flew farther from the field. The ARDS system has

an automatic relay function that allowed the aircraft to operate behind the mountain. A chase aircraft with another pod was used to relay the real-time data.

5.1.10 a. Unmanned Air Vehicle (UAV) - Medium Range Unmanned Aerial Vehicle (MR UAV), BQM-145A: The MR UAV was a program conducted by the Navy and flown at the AFFTC to demonstrate the capabilities of the BQM-145A Medium Range UAV. This vehicle, built by Teledyne Ryan Aeronautical, is intended as a reconnaissance platform for operation in high threat environments. Vehicle navigation is provided by a GPS-aided Inertial Navigation System (INS) whose data is telemetered to the ground in real-time. Range Safety systems consists of a 319-92 compliant FTS with position data provided by G-Band radar (beacon) track, FAA altitude encoding transponder and GPS position display. Per Range Safety requirements, a minimum of two tracking sources are required for launch of the UAV with a minimum of one source required for continuation of the mission. GPS as considered a suitable single tracking source as long as the data was validated by comparison with radar or IFF prior to loss of those assets.

The ground track was determined prior to flight and the route was flown on another aircraft using the GPS coordinates. This flight verified that the route was clear of population areas. The project also flew the route in simulation at their facilities. All parties agreed to the route and the profile was placed on the displays using the Flight Map program from the National Marine Electronics Association.

The test program was a success with the vehicle never straying off course and recovery occurring as planned.

Lessons Learned:

- The program flew a rehearsal flight as a captive missile under a F-4 aircraft. This caused numerous dropouts of data due to blanking of the satellites by the carrier aircraft and by multi-path problems. A better way to perform a captive carry mission is to have additional GPS antennas on the carrier aircraft and feed the GPS information to the vehicle.
- Flying the GPS track with another aircraft prior to the test, cleared the way to develop a route that met program requirements, as well as for range safety.
- Comparisons of GPS position and tracking accuracy with the instrumentation radar and Identification Friend or Foe (IFF) have shown that GPS provides an excellent position source with superior track quality. When compared to the IFF transponder, the GPS data is by far the better tracking source showing no false targets or loss of track.

5.1.10 b. Unmanned Air Vehicle (UAV) - Miniature Air Launched Decoy: The MALD is a program conducted under the auspices of the Defense Advanced Research Projects Agency (DARPA) to develop a small decoy vehicle capable of extended cruise operations. This vehicle needed to be launched from a fighter type aircraft in an operational scenario. Teledyne Ryan Aeronautical Inc., produced two vehicles each configured with a commercial off the shelf CA code GPS receiver for navigation. Vehicle flight tests were planned for a remote area of the

AFFTC range where ground based instrumentation and tracking systems are not available. After a review of the vehicle design, the AFFTC Range Safety Office agreed that the real-time display of vehicle performance measurements and position as derived from GPS data in the telemetry downlink would be satisfactory for Mission Flight Control purposes. GPS quality and status displays were also provided to the Range Safety Officer (RSO). A mobile telemetry and Flight Termination System (FTS) van was deployed to the test area and several missions were conducted with the RSO monitoring the vehicle using GPS as the sole range safety data source.

Lessons Learned: GPS provided excellent tracking information. The only problem noted was poor GPS reception prior to launch due to shadowing from the launch aircraft's wing.

5.1.10 c. Unmanned Air Vehicle (UAV) - Predator UAV: The Predator program is an ongoing program that involves both testing of the vehicle as well as testing of payloads and sensors. The Predator is a Remotely Piloted Vehicle (RPV) that is controlled either by a line of sight C-band link or a satellite KU-band. The vehicle's navigation is controlled by a Primary Control Module (PCM). This PCM communicates with a Litton LN-100G INS/GPS unit as its primary source of navigation. If this system were to fail, the PCM has a second GPS receiver internal to the PCM. This second system has its own antenna and is solely a GPS positioning and navigation system. It is not aided by an INS and can be used to check the aided INS for any drift.

The Predator and its variants have not encountered a loss of navigational guidance due to GPS anomalies. Because the second GPS receiver can be used to verify position, it has a built-in redundant system. The vehicle has lost link with the ground and has performed its pre-programmed GPS loss link procedures.

Lessons Learned: The second GPS unit with its own antenna in the PCM gives an additional level of confidence in the navigational system.

5.1.11 Smart Munitions (SM) - Miniaturized Munition Technology Demonstration Program: The Miniaturized Munition Technology Demonstration (MMTD) vehicle was one of several weapon systems with GPS that have been tested at Eglin in recent years. The air-launched weapon weighs approximately 277 lbs and is designed to destroy hardened targets. The weapon has a flight termination system which severs the aft control section. The MMTD weapon includes a Rockwell GEM-3, 5 channel GPS receiver coupled with a Honeywell IMU. Primary track for Range Safety was provided by Range radars, but the GPS data was displayed as a secondary tracking source.

Lessons Learned:

- Approximately 4 MMTD flight tests were conducted at Eglin. The GPS was an excellent source of position data. No significant problems were encountered with using GPS.
- Though not necessarily on this test program, it was noted by Eglin personnel that formats for the GPS data have been difficult to work with, resulting in a significant amount of programming and processing for display.

5.1.12 Ordnance Fusing - Reentry Body Impact Fuze Flight (RBIFF): The Reentry Body Impact Fuzing Flight (RBIFF) flew in February 1997 at Nellis Range Complex in Nevada. This research and development flight test consisted of a two-stage rocket system configured to fly in a "pile driver" mode so as to provide impact velocities in excess of 9,000 ft/sec. The objective of these two flight series was to conduct high speed fuze tests into both a soft and hard target for the U.S. Navy. The rocket system, a Strypi XIIR (Castor-I with two strap-on Recruits and a Thrust Vector Control guided Orbus-I second stage) was launched from the new Sandia Wahmonie Launch Facility at the DOE Nevada Test Site (NTS). Second stage/payload body pointing was accomplished with a cold gas Attitude Control System (ACS). Guidance to the target by the second-stage was assisted with a closed loop Interstate Electronics Corporation (IEC) GPS aided IMU navigator. The Interstate receiver was Model NGR and utilized three separate antennas during pre-launch and in-flight GPS functions (launcher mounted patch antenna, 2nd stage belly band antenna, and payload base mounted antennas.) Terminal steering was provided by a Lockheed-Martin Moving Mass Control (MMC) system while the payload was spinning at about 4 Hz. While the first stage was unguided, the guided second-stage Orbus employed both a flight safety command enable function on motor ignition and a Flight Termination System (FTS) capability (during motor burn). Nominal trajectory apogee was about 725,000 ft with a payload range at impact of about 66 nm. Safety analysis, performed by Sandia, was critical because of four factors: 1) non participant population near range boundaries, 2) off-range capability of the Orbus motor, 3) test participants located less than 4 nm from the target impact area, and 4) the number of USAF high value sites located inside the booster 3-sigma area. The approach to range safety was a hybrid method utilizing a standard 3-sigma dispersion analysis for the unguided first-stage with a more sophisticated probabilistic approach for the guided second stage. The launcher settings were corrected for winds using standard wind weighting methods. However, due to the near vertical elevation angle (86 degrees no wind), the launcher settings were particularly sensitive to winds and the test had to be delayed for several weeks due to moderate to high winds at the launch site (ballistic wind in excess of 12 ft/sec).

As part of the ground-based range safety software, pointing algorithms similar to on-board flight software, are used to calculate upper stage pointing angles, and then compared with the actual telemetry data as measured by the on-board IMU. These angle calculations were part of the information used in real-time to verify vehicle attitude and positioning for enable prior to Orbus ignition. Input to the ground solution was to be radar as primary with a telemetered GPS only output from on-board receiver as the backup. When the ground impact prediction matched the on-board solution based on IMU information, then an enable was sent. Vehicle IMU attitude was to be verified indirectly on the ground prior to enable by comparison of derived strapdown IMU earth-fixed state vectors with those reported by ground radar tracks or, as a backup, on-board vehicle GPS.

Performance of the system after launch was nominal for the most part with some anomalies. The booster did not respond completely to winds during the initial burn. Indications are that this problem was possibly the result of an asymmetric release of the Recruit motors. The payload section carried a C-band beacon to assist in radar tracking. A failure by the launch area radar to get positive lock at liftoff because of plume attenuation, resulted in no handover to the other three over-the-horizon radars and no radar track was obtained throughout the flight. Good TM data provided GPS receiver verification of IMU information during flight for the flight safety

enable. Post flight analysis indicates that an error in the GPS solution algorithm software caused the GPS system to rely on on-the-horizon satellites only resulting in a less accurate vertical assessment. This error resulted in an impact prediction solution 5000 ft. below the target surface. As a result of the GPS not properly updating the IMU during flight, a miss distance of about 1000 ft. was observed at impact. From a flight safety perspective, the GPS solution provided the critical inputs for the real-time safety control. A second RBIFF mission is planned for September 1997.

Lessons Learned:

- Within reason, GPS can be used in real-time to indirectly verify IMU attitude information.
- In future RBIFF flight testing, telemetry data from the on-board IMU will be used to help point radars.
- A separate downlink of GPS can be used to provide a satisfactory verification that the on-board IMU is working properly so that a successful real-time 2nd stage enable decision can be made despite problems with ground radar tracking.

5.1.13 Artillery - The Hardened Subminiature Telemetry and Sensor System (HSTSS) program is conducting a study to identify the performance of a miniaturized tightly coupled GPS receiver and an inertial measurement unit (IMU) for a high dynamic 2.75 inch rocket or missile. A COTS receiver will be coupled to automotive-like microelectronic systems (MEMS) accelerometers and angular rate sensors to prevent the loss of lock of the GPS receiver. A data rate of 10 Hz is required from the navigation solution. This effort is sponsored by STRICOM and technically coordinated by ARL's Weapons and Material Research Directorate at APG. The contract effort is with the Defense Microelectronics Activity's (DMEA) Advanced Technology Support Program (ATSP) with Rockwell Collins.

The ARL initiative is of importance because the GPS module will be adaptable to a wide variety of applications that encompass most high dynamic missile scenarios. It may be possible to type certify the HSTSS GPS/IMU module to rigid safety standards. Information will be shared as the development and demonstration phases of the program proceed.

Lessons Learned: On-going efforts to develop GPS systems for a specific purpose has the potential for a wide variety of applications.

5.1.14 Artillery - GPS Auto-Registration System: GPS Auto-Registration system will provide tube artillery with improved effectiveness and registration capability without the need of a forward observer. It consists of a projectile mounted translator and a small ground receiver system. The system is designed to determine projectile position in flight, calculate the actual trajectory and compare that with the predicted trajectory. The system then determines artillery-firing corrections and provides the corrections to the firing platform, to be used for subsequent firings and missions. The total system accuracy is required to be 40 meters (CEP), and the GPS position information is required to be better than 5 meters (SEP). The translator is housed in the volume of a standard artillery fuze (approximately 9 cu. in.) and contains two conical wrap

antennas, a reserve lithium battery, and the translator MMIC electronics circuitry. The translator has been designed to withstand 155-mm howitzer environment (16,000-g acceleration and 275-rps spin), and has been successfully fired at both the Yuma and Aberdeen Proving Grounds. The translator down link is at S-band. There are two versions of the GPS differential-based ground receiver system currently in use; a software receiver/post-processing system, and a hardware-based real-time receiver. Both systems are small, portable units about the size of a personal computer and provide position and velocity information. Fielding plans call for incorporation of the ground system into existing platforms (such as the M109A6 Paladin) and fire control. Current translators are C/A code, with P(Y) code analog and digital versions scheduled for testing FY98.

Lessons Learned: A series of live-fire 155-mm howitzer testing has been completed, with six of nine translators performing as expected. Failures were due to mechanical packaging of electronic components. The failures were analyzed early in the testing, corrected, and the final firings were completed without failure.

5.1.15 Artillery - EX-171 Extended Range Guided Munition (ERGM): The Extended Range Guided Munition (ERGM) is a rocket-assisted, steerable projectile which utilizes GPS/INS guidance for precision delivery from Navy surface ships into enemy shore defenses. The ERGM is under development by Raytheon TI Systems (RTIS) for the Naval Surface Fire Support (NSFS) Program Office, PMS-429. The Naval Surface Warfare Center/Dahlgren Division (NSWCDD) Dahlgren, VA serves as the NSFS Technical Direction Agent. The ERGM is to be launched from the Navy 5-Inch/62 caliber MK 45 MOD 4 Gun Weapon System. Initial operating capability for the ERGM is scheduled for FY01 on the DDG 81.

Initialization parameters, such as clock synchronization, target location, GPS ephemeris and almanac, are loaded into the projectile just prior to gun launch via a magnetically coupled interface located in the MK 45 loader drum. A portable test set will be used for initialization during land-based testing. The round is then loaded into the gun along with a powder charge to meet a 20-minute launch window for land-based testing or a 2-minute launch window for at-sea testing. Following firing and exit from the gun muzzle, tails fins deploy and a solid propellant rocket motor ignites to propel the projectile toward the specified target. The round initially leaves the gun spinning as a result of barrel rifling. Projectile spin is neutralized by the action of a mid-body spin-decoupling obturator band and tail fin and canard deployment. The projectile has a maximum range requirement of 63 nmi. Environments of up to 10,600 G's nominal and 12,500 G's proof are experienced during gun launch. The projectile is 5" in diameter and 61 inches long. The payload features 72 EX-1 dual purpose submunitions, a Navy variant of the Army-developed XM-80 submunition.

Navigation utilizes an Interstate Electronics Corporation (IEC) direct P(Y), fast acquisition GPS receiver tightly coupled with an Inertial Navigation System (INS) to obtain mid-flight corrections to guide the munitions payload to the specified target munitions dispense location. GPS-INS guidance is critical to meet the specified target location error at all ranges. The vehicle INS contains a three-axis fiber optic gyroscope and accelerometers. Wideband correlation using a Discrete Fourier Transform processing scheme is utilized to offset frequency uncertainties at launch. The GPS is hardened against battlefield countermeasures by means of

top and bottom antenna selection. Lateral antennas are used to provide home on jam functions. A system of 4 patch antennas, mounted at 90 degree intervals circumferentially are used in this process.

Vehicle internal space is extremely limited. Initial guided flight rounds will utilize an instrumentation payload containing a Flight Termination System (FTS) and telemeter to provide range safety in lieu of the tactical submunition payload. If a signal to terminate flight is received, the FTS will command the canards to spin up the projectile, the round is expected to go ballistic foreshortening flight range. Simulation of this process shows that the munitions can then be contained in safe areas of WSMR. This concept is currently under review at the involved Ranges. It is proposed that projectile position be tracked for range safety using the GPS coordinates downlinked via telemetry. Once the performance of the guidance system has been validated, the payload will be transitioned from the instrumentation package to the submunitions and range safety will be maintained via on-board software which monitors the health of the projectile subsystems.

Lessons Learned: A technology demonstration of a gun-launched GPS receiver was successfully completed in April 1997 at Yuma Proving Grounds. The Rockwell-Collins GPS acquired a four satellite P(Y) track in 14 sec and navigated to impact. Range was 19nmi.

5.2 Overview of Lessons Learned

GPS is being adapted to a wide variety of uses. Ranges have supported operations using GPS translator and receiver equipment and can expect to support a wide variety of GPS systems, including inertially aided GPS. The following lessons learned overview has been developed from specific program inputs, as well as Range experiences.

- **Use of GPS Translators** - GPS translator technology is mature and support of flight safety has been proven on high performance vehicles. Use of miniaturized digital translators and ground processors allows GPS to be integrated into most vehicles and most Ranges. The integration is similar in scope to adding a conventional telemetry transmitter on the vehicle and telemetry receivers at Range telemetry acquisition sites.
- **Use of GPS Receivers** - GPS receiver technology is progressing at a rapid rate, and commercial receiver capability has outstripped available DoD modules. Commercial Off-The-Shelf (COTS) receivers can be readily integrated into many vehicles and scenarios for flight safety support. The integration is similar in scope to adding a telemetry transmitter on the vehicle. Modified COTS GPS receivers can provide adequate flight safety support even on high dynamic vehicles when coupled to a ring antenna. There may be difficulties in adapting some commercial receivers for use with patch antennas because the typical receiver processor does not have the algorithms to compensate for moment arm effects induced by the antenna system as the vehicle maneuvers. (The ground based translator processor; however, has such algorithms.) By coupling the receiver with an IMU or accelerometers, receiver data degradation induced by moment arm effects can be circumvented.

- System Design Considerations - Users are adapting GPS receivers for on-board use in applications such as navigation, guidance and control, etc. In some cases, the user design is inappropriate to flight safety support, so a stand-alone module must also be provided on the vehicle to support flight safety. This duplication could be avoided if the user module included the design features illustrated in Figure 5-1.

These design features include:

- Use of an IMU (or possibly just accelerometers) to bridge receiver dropouts
- Optimal loop aiding with loose coupling to improve GPS receiver performance
- Downlink raw measurements to enhance system integrity, reliability and accuracy
- Transmission of low bit rate IMU/GPS receiver data to conserve power and bandwidth
- Dual independent composite data links
- Independent power supplies (not shown)

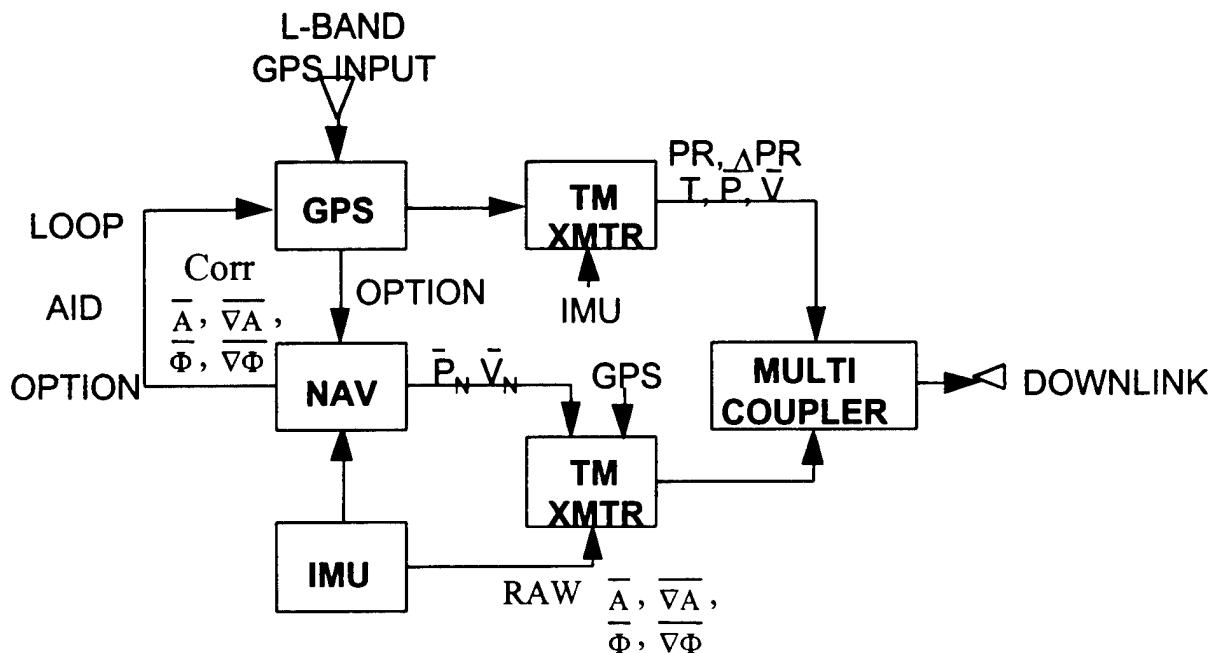


Figure 5-1.

- Ground Processing of Raw Data - Raw data telemetered from GPS receivers (pseudorange and delta pseudorange) and IMU/INS ($\bar{\varphi}, \bar{\nabla \varphi}, \bar{A}, \bar{\nabla A}$) can be processed by the Range to improve the GPS and INS system performance by increasing system reliability and accuracy, and may satisfy the metric data requirements for flight safety. Users should, as a minimum, include access points for telemetry relay of raw data.
- Downlink Reliability - It is important that all vehicle telemetry data not be lost due to a single point failure of the telemetry relay and display equipment. GPS data should be transmitted on an independent vehicle telemetry link with ground telemetry acquisition sites

spatially separated, and redundant relay, processing and display provided for GPS and critical vehicle telemetry data.

- Data Health and Quality - A measure of data health and quality should be provided with the GPS based state vectors. The quality data should allow display of a definitive estimate of accuracy.
- Evaluation of GPS System Performance - It is important to properly test and evaluate the performance of the GPS system to assess if it meets the Range's specific requirements.
- Dynamic Simulations - Flight tests of GPS systems will normally provide performance verification under normal vehicle flight conditions. From a flight safety perspective, information is also needed for possible conditions of abnormal flight. Such information can be readily provided by simulations that can be conducted by DoD laboratories. It should be possible for these laboratories to make simulation tapes that can be played back at both the user facilities and at the Ranges to validate system performance. Such tapes could also be used by the Ranges during pre-mission checkout for the conduct of end-to-end readiness testing.
- Pre-Mission End-to-End Testing - Pre-mission Range end-to-end testing, together with simulations can be used to identify potential dropout intervals or problems with Range support configuration.
- User Coordination With the Ranges - Early coordination between users and Ranges to determine the data needed for flight safety may make it practical to eliminate dedicated flight safety tracking aids on the vehicle. Examples include flight safety access to raw GPS and IMU/INS measurements.
- Use of C/A Code - Use of C/A code is significantly simpler to implement and use at the Ranges and should be used whenever C/A code accuracy is sufficient. When additional corrections are required, use of raw data with differential correction can be considered.
- Duplication of Effort - In past government programs, safety related subsystems (flight termination, radar transponder, telemetry, INS) have been developed over again for each new program at great expense. Although "one size fits all" is not being advocated for GPS based future flight safety metric support subsystems, the coordination of requirements and design solutions is advocated, so that the design, development and certification expense can be minimized. Again, user coordination with the Ranges early in the program planning phase to determine the type of data needed could have big payoff by somewhat standardizing design.
- Monitoring for Jamming and Spoofing - Though not expected to be a major problem for flight safety, it is important that Ranges monitor for jamming and spoofing.
- Autonomous Flight Safety - There is an emerging trend to use GPS data on-board the vehicle to determine if the flight is proceeding safely. When required, flight termination would be initiated autonomously without a "man in the loop."

CHAPTER 6

GPS FLIGHT APPROVAL PROCESS

This chapter provides a process by which the ranges can evaluate GPS systems as a metric data source for real-time flight safety decision making. The key to this process is the evaluation and testing of the GPS system and the use of dynamic simulations.

6.1 Overview

The intent of this chapter is to identify a process by which GPS systems can be approved by the ranges for use as a real-time safety data source. The process is outlined in Figure 6.1 and begins with the user providing information on the vehicle and GPS systems. The range evaluates this information to determine if the GPS system can reliably provide the metric data needed to make real-time safety decisions. The most critical aspect of evaluating the GPS system for flight safety use will be its performance under both nominal and errant vehicle environments. Prior flight test history or laboratory simulations will be essential to this evaluation. Once the range approves the GPS system for flight, the mission support, which includes range readiness checks and pre-mission testing, will provide an end-to-end evaluation of the integrated vehicle/range system. This process is similar to processes already in place at the ranges for approving other metric tracking sources such as radar transponders. The biggest difference between this process and that historically used for radars will be the expanded use of simulations to evaluate GPS system performance under dynamic (simulated) flight conditions for initial flight applications.

The ranges have been struggling with the question of how GPS will be used as a flight safety tracking source for many years. The ad hoc group found that ranges have approached this question in different ways. Some ranges will do a portion of this "approval process" and allow the GPS to be used for flight safety on initial flights as long as a radar transponder is also flown on some predetermined number of flights. However, the group found that more can be learned from the dynamic simulations that are discussed in the recommended approval process than from the dynamic performance of the GPS system on a limited number of nominal flights. The GPS Ad Hoc group believes that if this process is followed, and the particular GPS system is approved and end-to-end tests of the integrated system are successfully completed, there may not be a requirement for a backup or tertiary metric tracking system on initial GPS system flights.

The GPS Ad Hoc group is not advocating that flight safety accept GPS as the only tracking source or that ranges not require two independent tracking sources. In most cases, the requirement for two independent tracking sources will necessitate that a radar transponder track be one of those sources. However, as discussed in previous sections of this document, a properly designed GPS system could satisfy both the user navigation function and the requirement for two independent tracking sources.

This approval process is designed to ensure coordination between the range and user from the early system design and development stages through real-time and post-mission support. As we have discussed earlier, the implementation of flight safety requirements varies from range to range and program to program depending on specific mission requirements. Therefore, this process should be tailored as necessary to satisfy safety requirements at each particular range. The process is discussed in greater detail in the following sections.

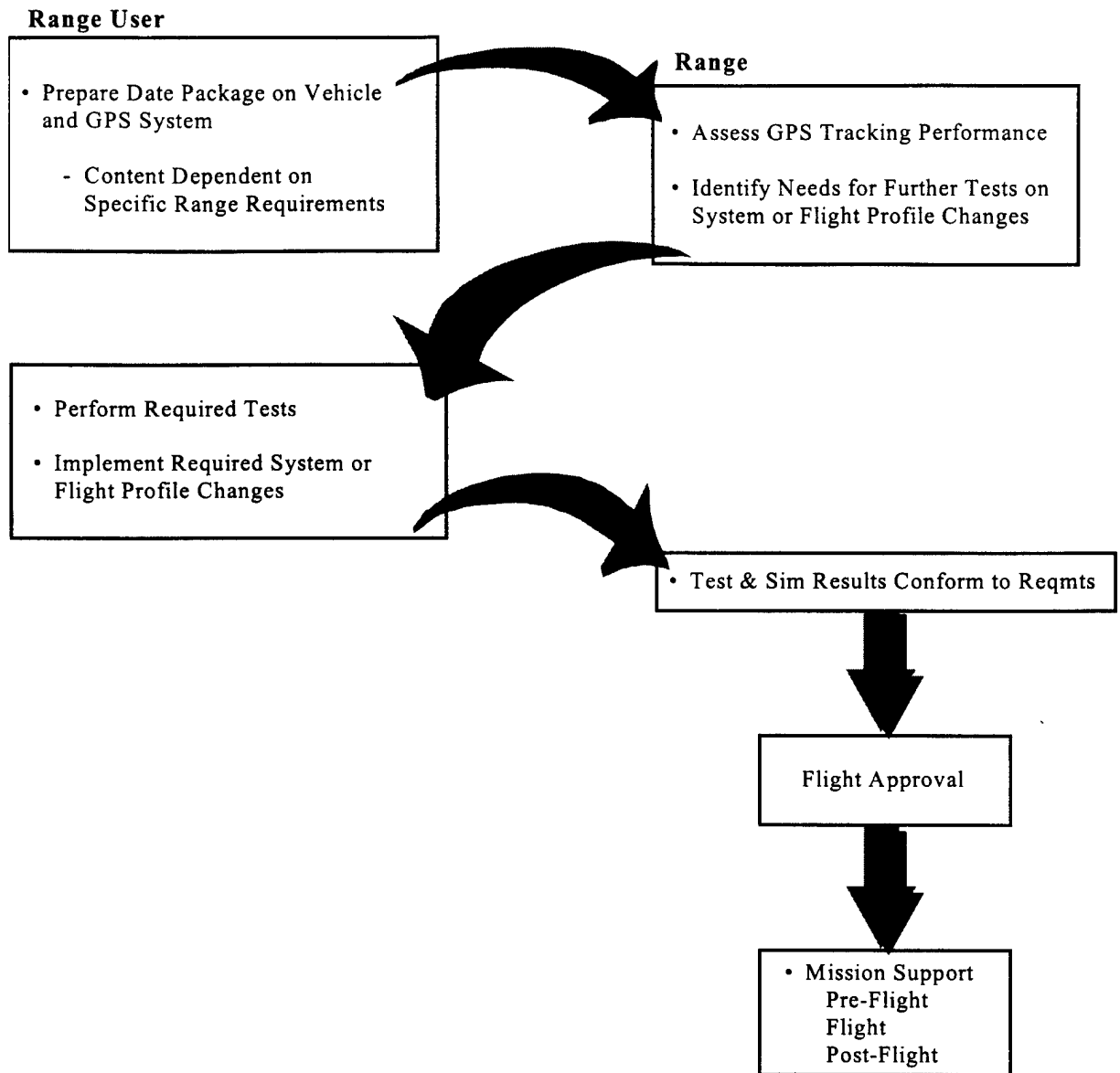


Figure 6-1. GPS Metric System Certification

6.2 Flight Approval Process

Flight safety's fundamental requirement is the protection of life and property, but it is also concerned with mission success. Range Safety Officers rely on information from various metric-tracking sources to make critical decisions in real-time, and must have confidence that the tracking aids will perform reliably in the dynamic environments experienced during vehicle flight. The flight approval process discussed in this section is intended to ensure the range receives all the proper information/data needed to gain confidence in the GPS system being used. This section is also intended to help the user understand the process and facilitate the coordination of requirements.

- Vehicle and GPS Data Package: The process begins with the user submitting a Data Package describing both the vehicle performance and the particular GPS system capabilities. The vehicle information shown below would normally be required by the range to perform the flight safety test management function and/or to evaluate a particular metric tracking aid.

- a. Vehicle Nominal Flight Trajectories - This includes nominal and ± 3 sigma trajectories. Specific formats for this information are range dependent.
- b. Vehicle Failure Modes, Failure Trajectories, and Maximum Maneuver Rates - This includes a description of failure modes and probabilities and associated trajectories (often referred to as worst case turns). This information is evaluated to define flight termination requirements and to identify other safety test management requirements. Specific formats for this information are range dependent.
- c. Nominal and Worst Case Flight Environments - Vehicle environments include those listed below. Of special interest would be those environments to which the GPS would be subjected.

Altitude
Temperature
Humidity
Vibration
Shock
Jerk
Acceleration
Rain
Sand/Dust
Salt Fog
Electric Power Variation
Electromagnetic Interference

d. GPS Configuration - Description of all GPS tracking aid hardware, including interfaces to other systems (i.e., IMU), antennas, downlink components, and physical location of all components. A functional block diagram should be included.

e. GPS Performance Characteristics - Description of GPS system capabilities:

- Position, Velocity Solution Update Rates
- Measurement Time Tag
- First Acquisition Time (Time to First Fix)
- Reacquisition Time
- Figure Of Merit (or other Measure of Accuracy)
- Satellite Selection Information
- Lever Arm Dimensions relative to IMU or INS
- Receive Antenna locations, Patterns, and Gain
- Data Latency

f. Laboratory and Flight Test Results - Results of laboratory testing, flight simulations, and any flight-test history and performance should be provided.

g. GPS Data Downlink - Description of GPS downlink method, data rates, bandwidth, RF power, and antenna patterns, gain and location.

- Assess GPS Tracking Performance: The ranges will then assess the vehicle information and GPS performance characteristics to determine if the defined GPS system can provide the necessary data to reliably make real-time decisions. The ranges may identify additional testing and/or may find that vehicle flight profile changes may be necessary to safely accommodate the mission. Again, this process is no different than what is currently done at most ranges. The biggest difference is the use of simulations to assess GPS performance.

The ad hoc group found that dynamic simulations can be a very effective method for estimating GPS performance and gaining confidence that GPS will function under vehicle nominal and failure conditions. The group suggests that evaluation of the GPS system be done using vehicle nominal trajectories, as well as failure (worst-case turn) trajectories. In addition, if the GPS system is coupled with another source such as an IMU, the simulations should model the GPS/IMU coupling and validate the GPS/IMU processing. These dynamic simulations could also be used to validate range processing and display functions and as part of end-to-end functional pre-launch checks.

- Perform Required Tests: As mentioned above, testing and simulation of GPS under vehicle nominal and failure conditions is the key to gaining confidence in GPS as a flight safety data tracking source. Therefore, the information provided by the user with respect to item f. above is very important. If the user has already subjected the GPS system to some type of environmental qualification program, laboratory testing, simulations, or actual flight, this information and results should be provided to the range as part of the initial data package.

The results will be evaluated by the range and may be sufficient to provide the necessary confidence that the system will work reliably.

If the range defines additional testing requirements, this testing could either be conducted by the user or possibly at one of several government facilities. The GPS Joint Program Office (JPO) at Los Angeles Air Force Base has established a Center of Expertise (COE) consisting of several test agencies that have unique GPS test capabilities. These test agencies include the 746th Test Squadron (Holloman AFB), the Naval Command, Control, and Ocean Surveillance Center (San Diego), the Electronic Proving Ground (Ft Huachuca), and the Naval Research Laboratory. These facilities either currently have or are establishing capabilities to conduct the type of GPS simulations discussed in the previous paragraphs.

The GPS JPO has also sponsored these test agencies in the development of a Core Test Plan (reference 13) for GPS receivers, IMU systems, and receiver/IMU systems. This test plan identifies testing objectives and test/analysis methods for performing environmental qualification, functional, and performance evaluation tests on these types of GPS systems. The ad hoc group has reviewed this test plan and believes that it could form the basis for developing a test plan for GPS systems used for flight safety support. The GPS JPO has agreed to work with and support the RCC in developing test plans applicable to flight safety.

- Verify Test or Simulation Results: The ranges will verify GPS tracking aid performance based on user provided test and simulation results, or any other testing that may have been done by the user or government laboratories. This verification may be iterative until acceptance is achieved.
- Flight Approval: Flight approval is given by the range to use the particular GPS as a source for flight safety decision making.
- Mission Support: The mission support activities, though shown in Figure 6.1 to follow Flight Approval, are in essence part of the flight approval process and are discussed in the following section.

6.3 Mission Support

Mission support, as discussed in this guideline document, consists of four phases: Range Readiness, Pre-Flight, Flight, and Post-Flight. The Range Readiness Phase involves those activities primarily done by the range to prepare for the pre-flight countdown. The Pre-Flight Phase is defined to begin after (1) the user has completed testing the GPS modules to be flown, has installed the modules on the flight vehicle and is ready to interface with the range, and (2) the range has developed, tested and certified the hardware/software required to acquire, transfer, process and display for flight safety the required GPS derived information. User requested displays for real-time flight performance evaluation are also tested during both the Range Readiness and Pre-Flight Phases. The Flight and Post-Flight Phases are intuitive, with the Flight Phase essentially beginning when the vehicle or test article is launched and the Post-Flight Phase beginning when the flight or test is complete.

6.3.1 Range Readiness Phase. The user and range should coordinate in the early stages of the program to ensure that all range and user requirements can be achieved. The range Readiness Phase includes several actions:

- **Hardware-in-the-Loop (HWIL) Testing:** HWIL tapes have been used by the ranges for many years to validate the processing of inertial guidance data for flight safety. These tapes are typically provided by the user. The dynamic simulations discussed earlier in section 6.2 could not only serve to evaluate the performance of the GPS system, but can also be used by the ranges as HWIL tapes to validate proper processing and display of GPS data.
- **Scheduling:** Using GPS as a data source for the range and for flight safety will require an additional effort above the normal range scheduling procedures. Coordination with frequency management is important to identify not only the GPS frequencies, but also any possible interference or source of jamming.
- **DOP Forecasts:** A set of DOPs along the nominal trajectory should be calculated by the range prior to the scheduling of a mission and compared to the user furnished DOPs. As discussed in Chapter 4, these DOPs should reflect the vehicle's antenna pattern and nominal attitude. The range should also monitor the health of the GPS constellation (especially near launch). There are several resources available that can provide up to date satellite health information, including TECNET.

6.3.2 Pre-Flight Phase. Prior to launch countdown, readiness testing of the GPS module and range interface will be required. GPS signals (real or simulated) will be input to the GPS module and its output will be acquired by the range, recorded, transferred, processed and displayed in the Flight Safety Center for a final end-to-end readiness test. This requires that the user provide the capability to input appropriate signals to the GPS modules on the vehicle during pre-flight. During countdown, various parameters identified by range and flight safety personnel will be monitored to ensure continued integrity. The GPS reference receivers should be monitored by the range during countdown to detect any changes in satellites status. Any detected change should be accepted by the vehicle's GPS module processor and be verifiable prior to countdown completion.

6.3.3 Flight Phase. Range resources are scheduled to provide the data acquisition coverage, recording, processing, data products, and information displays requested by flight safety and the user. GPS solution accuracy estimates and satellite selection and health should be monitored by flight safety personnel during the portion of the flight which requires flight safety management, whether that be powered flight or some other flight interval with the potential to result in a hazardous situation.

6.3.4 Post-Flight Phase. For nominal flights, scheduled data products will be produced from the recorded GPS measurements. In the event of a flight anomaly, special processing may be performed for the user or range to support anomaly analysis.

SUMMARY AND RECOMMENDATIONS

The primary objective of the GPS Range Safety Applications Ad Hoc group was to evaluate the use of GPS as a real-time flight safety data source and to provide guidelines for its implementation at the ranges. Our findings indicate that GPS technology, as it stands today, is capable of providing a "more than adequate" data source for safety decision-making. The group found that some ranges are already using GPS as a tracking source on various types of vehicles ranging from Submarine Launched Ballistic Missiles (SLBMs) to Unmanned Air Vehicles (UAVs). In some cases, ranges are using GPS as the primary data source. All ranges will most probably be using GPS as a primary flight data source in the very near future. The group also found that many users are implementing GPS as part of their guidance and navigation systems. When properly designed, these user systems can also provide data for flight safety purposes. When compared to other metric sources, GPS has many advantages; however, no single data source, even GPS, provides a complete safety solution under all test conditions. Therefore, it is wise for range planners to consider a balance of instrumentation, including GPS, radar, inertial data, and optics.

The GPS Ad Hoc Group recommends that ranges implement GPS as a flight safety real-time metric data source. The basic process described in Chapter 6 should be followed to ensure proper evaluation of the GPS and verification of the integrated vehicle/range system. Though this process and the guidelines document goes a long way toward implementing GPS as a safety data source, the specific standards or requirements for testing have not been fully identified. The Range Safety Group was briefed on this guidelines document and the ad hoc group's findings at their October 1997 meeting (see references 14 and 15). At this meeting, the ad hoc group recommended a follow-on effort/task to develop these necessary standards and requirements:

- Standards for environmental qualification, functional, and performance testing of GPS system.
- Requirements for conducting GPS dynamic simulations.

The Range Safety Group accepted this recommendation, and at the writing of this document a task proposal was being formulated to address this task.

GPS Range Safety Applications Ad Hoc Group

Name	Organization and (service affiliation)
Ms. Leticia Sanchez, Chairperson	White Sands Missile Range (U.S. Army)
Mr. Rick Navarro, Vice Chairperson	Pt. Mugu Naval Air Warfare Center Weapons Division (U.S. Navy)
Mr. David Donahe	White Sands Missile Range (U.S. Army)
Mr. Robert Greenberg	30th Space Wing, Plans & Programs, Vandenberg AFB (U.S. Air Force)
Mr. Fred Grimes	ITT Federal Systems Corp., Vandenberg AFB (U.S. Air Force)
Mr. Dex Hansard	China Lake Naval Air Warfare Center Weapons Division (U.S. Navy)
Mr. Norman Keegan	Aerospace Corporation, Los Angeles AFB (U.S. Air Force)
Mr. Robert Pickett	ACTA Inc., Vandenberg AFB (U.S. Air Force)
Mr. Leonard Roen	412th Test Wing, Edwards AFB (U.S. Air Force)

Other Participants

Mr. Antonio Avalos	White Sands Missile Range (U.S. Army)
Dr. Richard Brooks	ITT Federal Systems Corp., Vandenberg AFB (U.S. Air Force)
Mr. Eric Byrd	Space & Strategic Defense Command, Huntsville (Kwajalein Missile Range safety) (U.S. Army)
Mr. Michael Campbell	45th Space Wing, Eastern Range, Patrick AFB (U.S. Air Force)
Mr. Cory Cather	30th Space Wing, Western Range, Vandenberg AFB (U.S. Air Force)
Mr. Kelvin Coleman	Federal Aviation Administration, Office of Space Transportation, Washington, DC (FAA)
Mr. Burt H. Colt	Range Applications Joint Program Office, Eglin AFB (U.S. Air Force)
Mr. Jerry Esquibel	Space & Strategic Defense Command, Huntsville (Kwajalein Missile Range safety) (U.S. Army)
Mr. Kingston George	ACTA Inc., Vandenberg AFB (U.S. Air Force)
Mr. Nikos Himaras	Federal Aviation Administration, Office of Space Transportation, Washington, DC (FAA)
Mr. Antonio Palomino	White Sands Missile Range (U.S. Army)
Mr. Harold Reck	ACTA Inc., Vandenberg AFB (U.S. Air Force)
Mr. Don Sammon	White Sands Missile Range (U.S. Army)
Mr. Jon Williams	White Sands Missile Range (U.S. Army)
Mr. David Villalpando	Aerospace Corporation, Los Angeles AFB (U.S. Air Force)